Structural traverse across the Sierra Madre Oriental fold-thrust belt in east-central Mexico

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Structural traverse across the Sierra Madre Oriental fold-thrust belt in east-central Mexico

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ABSTRACT

The exposed structural geometry of the Sierra Madre Oriental foreland fold-thrust belt is quantified for an ~130-km-long strip along the Moctezuma River (21°N lat., east-central Mexico). The strip extends from the belt's leading edge in the east to its most internal continuous outcrops in the west, where the Cordilleran structures disappear beneath Cenozoic volcanic rocks.

The style of deformation is controlled mainly by the geometry and lithology of two major Cretaceous carbonate banks, El Doctor and Valles–San Luis Potosí, the long dimensions of which parallel the Cordilleran structural trend. The exposed shortening is concentrated on the platform margins (5 km on the eastern edge of the El Doctor bank and 10 to 12 km on either edge of the Valles–San Luis Potosí platform) and is characterized by thrust and fold nappes. The thrust faults cut across the platform-margin carbonates on <20°-inclined tectonic ramps that were partly steepened by imbrication or by subsequent folding but pass in the overlying, mechanically weak rocks nearly parallel to bedding. The interiors of the platforms appear relatively undeformed, whereas the regions between the two platforms (Zimapán basin) and between the eastern edge of the Valles–San Luis Potosí platform and the foreland are composed of flexural slip folds resulting from decoupling along several incompetent layers. The exposed bulk shortening measures 41.4 km or 25% for the entire traverse.

Retrodeformable sections of the subsurface structure down to basement result in a bulk shortening of 90.1 km or 40%. The subsurface deformation model for the western part of the traverse is thin skinned and has geometry similar to that on the surface. The model is very speculative in the eastern part, where the areal shortening calculated for thin-skinned models is much larger than is the exposed linear shortening. Balance was attained by inferring a blind thrust on an upper detachment in the Late Cretaceous which has a shortening of 20 to 30 km. It could also be attained, however, by intrabasement decoupling in a depth of 10 to 20 km.

Deformation is brittle in the eastern part of the belt, east of the Valles–San Luis Potosí platform, whereas igneous intrusion-controlled higher ductility characterizes the western part of the foreland fold-thrust belt.

INTRODUCTION

This paper presents results of a structural traverse which crosses the Sierra Madre Oriental foreland fold-thrust belt, the easternmost exposed segment of the Cordilleran orogenic belt in east-central Mexico, at ~21°N lat. (eastern Querétaro, southern San Luis Potosí, and northern Hidalgo States). The 130-km-long traverse mainly follows the Moctezuma River, the course of which is nearly perpendicular to the regional structural trend. Topographic relief, in places >2,000 m between the river valley and the nearby mountains, provides insight into different structural levels. The traverse extends from the flysch-filled Tampico-Misantla foredeep (Fig. 1) in the east to the westernmost continuous outcrops of sedimentary rocks, where the Cordilleran structures are covered by Cenozoic volcanic rocks. Parts of the foredeep and an Upper Jurassic–Lower Cretaceous volcanic terrane (Las Trancas Formation) are integrated into the fold-thrust belt.

The study has been carried out within a cooperative project of the Mexican National University (UNAM) and the University of Basel (Switzerland). It is based mainly on systematic structural reconnaissance mapping on 1:50,000-scale aerial photographs and topographic sheets, which were provided by the Mexican National Mapping Agency (INEGI) and which have only recently become available.

The traverse crosses two 1,500- to 2,000-m-thick Cretaceous carbonate banks, El Doctor and Valles–San Luis Potosí (hereafter abbreviated as VSP), which are separated by the Zimapán basin (Fig. 1). It has been convenient to use the two banks as references in discussion of the stratigraphy and structure for the following reasons. (1) The pre-Cretaceous stratigraphy is nearly unknown below the two platforms, and it differs on either side of the VSP platform; (2) the two platforms essentially control structural style in the study area.

It is the aim of this paper to quantify the geometry of the exposed structures and to extrapolate the geometry down to basement by means of volumetric constraints and subsurface data in the form of deformed area-balanced cross sections.

STRATIGRAPHY

Stratigraphy West of the El Doctor Bank and between the El Doctor and Valles–San Luis Potosí Platforms

The Las Trancas Formation (Segerstrom, 1962), the oldest exposed rocks, is volcanic-sedimentary in the west (El Chilar anticline, Figs. 2a and 3), where it consists of clastic and pyroclastic rocks intercalated with andesitic-dacitic lavas and less common limestone (Carrillo-Martínez and Suter, 1982, Chauve and others, 1985). East of El Doctor bank (cores of El Piñón and Bonanza anticlines, Figs. 1 and 2c), the formation is composed of pelagic limestone and phyllite with subordinate sandstone, graywacke, and pebble conglomerate. Quantity and size of detritus diminish upsection and toward the east (Wilson and others, 1955). The exposed part of the Las Trancas Formation is of Kimmeridgian to Barremian age (Carrillo-Martínez and Suter, 1982) and is thus corre-
Figure 1. Structural outline map of the Sierra Madre Oriental fold-thrust belt in east-central Mexico. The marked trace is that for Figure 11.
The Tamaulipas Formation in the Zimapán basin part, diachronous with those deposited on top of (Fig. 2c).

on the El Doctor bank (Fig. 2b) are probably, in existed between the El Doctor bank and the suggests that (1) some depositional relief still and Suter, 1982; Enos and Moore, 1983). This clasts can be found in the Soyatal Formation (Kiyokawa, 1981). Platform-carbonate exo-
 rifrative; in the usage of Carrasco, 1970). The entrance, to the latter is covered by volcanic rocks. These shallow-water platforms consist of piles of carbonates, ~ 1,500 to 2,000 m thick (El Abra Formation and El Doctor Formation, respectively; in the usage of Carrasco, 1970). The bank-edge facies are slightly outbuilding and include rudist knolls (Fig. 4) and nonparallel, discontinuously bedded bioclastic lime grainstone–rudstone–floatstone (Enos, 1974; Wilson, 1975; Enos and Moore, 1983). A series of irregular, alternating promontories and re-entrants characterizes the eastern edge of the El Doctor platform (Fig. 4). The promontories probably correspond to bioherms; the re-entrants, to the reef’s sediment-drainage network filled with carbonate debris. Very few outcrops of the western platform edge and foreslope of the VSP platform exist. It is very likely that these deposits are not missing stratigraphically, but that they are hidden below the Jiliapan and El Volantín thrust faults (Fig. 1). This is supported by the fact that all of the facies belts of the platform-basin transition zone are present southwest of Jiliapan (Fig. 3), where the platform margin is intersected obliquely by these two thrust faults. The deposits of the interior are mainly well-bedded limestones and contain evaporites (Guácumá Formation) south of Jacala (Fig. 1) and north of the Santa María River in Querétaro State. Subsurface extension of these evaporites is probably indicated by the large karst basins that exist on the platform in the study area (Fig. 3).

Figure 2. Schematic stratigraphic sections: (a) west of El Doctor bank, (b) El Doctor bank, (c) between El Doctor and Valles–San Luis Potosi platforms, (d) Valles–San Luis Potosi platform north of Highway 120, (e) east of Valles–San Luis Potosi platform. For the large variety of facies belts and microfacies types of the El Abra and El Doctor Formations, see Carrillo-Bravo (1971) and Wilson (1975). Explanations in the text.

The Soyatal Formation, the uppermost marine stratigraphic unit, is composed of partly rhythmically deposited shale and pelagic limestone with syndepositional folds and boudinage. The formation is of late Turonian to Campanian age. It is approximately correlative in time with the Ahuacatlán Formation of the area east of the VSP platform (Fig. 2e).

Stratigraphy of the El Doctor and Valles–San Luis Potosi Platforms

For the over-all geometry of the VSP and El Doctor platforms, the reader is referred to Carrillo-Bravo (1971). The VSP bank forms a 35-km-wide outlier where crossed by our traverse, but it is much wider farther northwest. The El Doctor bank may be an outlier of the VSP platform; its southeastern continuation toward the latter is covered by volcanic rocks.

These shallow-water platforms consist of piles of carbonates, ~1,500 to 2,000 m thick (El Abra Formation and El Doctor Formation, respectively; in the usage of Carrasco, 1970). The bank-edge facies are slightly outbuilding and include rudist knolls (Fig. 4) and nonparallel, discontinuously bedded bioclastic lime grainstone–rudstone–floatstone (Enos, 1974; Wilson, 1975; Enos and Moore, 1983). A series of irregular, alternating promontories and re-entrants characterizes the eastern edge of the El Doctor platform (Fig. 4). The promontories probably correspond to bioherms; the re-entrants, to the reef’s sediment-drainage network filled with carbonate debris. Very few outcrops of the western platform edge and foreslope of the VSP platform exist. It is very likely that these deposits are not missing stratigraphically, but that they are hidden below the Jiliapan and El Volantín thrust faults (Fig. 1). This is supported by the fact that all of the facies belts of the platform-basin transition zone are present southwest of Jiliapan (Fig. 3), where the platform margin is intersected obliquely by these two thrust faults. The deposits of the interior are mainly well-bedded limestones and contain evaporites (Guácumá Formation) south of Jacala (Fig. 1) and north of the Santa María River in Querétaro State. Subsurface extension of these evaporites is probably indicated by the large karst basins that exist on the platform in the study area (Fig. 3).

The base of the carbonate platforms is known only from a Petróleos Mexicanos exploratory well (Valle de Guadalupe-1, Fig. 1) north of the traverse, where the El Abra Formation is con-
cordantly underlain by the Pimienta Formation, and from outcrops near the southeastern edge of the VSP platform in the Amajac Canyon, where the El Abra Formation is concordantly underlain by −100 m of limestone of Tamaulipas lithology and by the Las Trancas Formation (Fig. 3). Where the Valle de Guadalupe-1 well was drilled, platform deposits had begun to accumulate in the Barremian (Carrillo-Bravo, 1971), whereas this stage is partly represented farther south by the Las Trancas Formation (Carrillo-Martínez and Suter, 1982). The lower part of the VSP platform north of the Moctezuma River, therefore, may be somewhat older than is the outlier farther south and than is the El Doctor bank (compare with Carrillo-Bravo, 1971, Fig. 9).

Locally in the traverse area, the platforms are overlain by the pelagic-detrital Soyatal Formation of late Turonian to Campanian age, where they were drowned by a major sea-level rise.

Figure 3. Tectonic map of the study area (southwestern part after Carrillo-Martínez and Suter, 1982). The marked traces are those of the sections of Figure 5. The names of the compressional structures can be found in Figure 1. (Note overlap in center.)
(Vail and others, 1977) during Turonian. Platform-carbonate production, however, probably lasted until early Campanian near the present site of Highway 120, where the lower part of the Soyatal Formation corresponds to the *Globotruncanana elevata* planktonic foraminiferal zone *sensu stricto* (Suter, 1984). In places farther north on the VSP bank, platform carbonate persisted until Maastrichtian (Tamasopo Formation, Carrillo-Bravo, 1971; Young, 1977).

**Stratigraphy East of the Valles–San Luis Potosí Platform**

The oldest exposed rocks (Huiznopala Formation, Fig. 2e) are gneisses of blastomylonitic texture (von Kuegelgen, 1958) that crop out in several basement windows in the Huayacocotla anticlinorium south of the traverse strip (Carrillo-Bravo, 1965). Detrital zircons from the Huiznopala Formation indicate a Precambrian sediment source; they yielded lead-alpha ages of $1210 \pm 140$ Ma (Fries and Rincón-Orta, 1965).

The rocks between the crystalline basement and the Middle Jurassic do not extend over the entire area. This is due to normal faulting (prob-
ably related to opening of the central Gulf of Mexico; Pindell, 1985) during Early and Middle Jurassic time. These rocks were partly eroded before the regional transgression of the Middle Jurassic and partly deposited as graben fillings. The pre-Cretaceous series of Figure 2e is fully preserved only in Jurassic grabens; the interval between the basement and the Tamán Formation is partly or totally missing on Jurassic topographic highs.

Above the crystalline basement, the sedimentary column east of the VSP platform (Fig. 2e) comprises (1) Carboniferous and Lower Permian flysch (Guacamaya Formation; Carrillo-Bravo, 1965), which crops out in the core of the Huyacocotla anticlinorium (Fig. 1); (2) sandstones (Huizachal Formation; Imlay and others, 1948) of Late Triassic (Silva-Pineda, 1963) to Hettangian age (Schmidt-Effing, 1980), which are exposed in the Amajac and Claro Canyons (Fig. 3) and also crop out elsewhere in the Huyacocotla anticlinorium (Carrillo-Bravo, 1965); (3) the marine Huayacocotla Formation (Imlay and others, 1948), consisting of marine shale and less common sandstone (partly turbidites) of Sinemurian-Pliensbachian age (Schmidt-Effing, 1980); and (4) the Cahuas Formation (Carrillo-Bravo, 1965), a red-bed series, which measures ~500 m in grabens, where it is in transitional contact with the underlyng Huayacocotla and the overlying Upper Jurassic formations, but which is absent on Jurassic horsts.

A transgressive series (Fig. 2e) is initiated by the Tepéxic Formation (calcarenites of Callovian age; Erben, 1956) and continues upslope concurrently with the pelagic Santiago formation concordantly with the pelagic Santiago age; Erben, 1956) and continues upwardly by the Tepéxic Formation (calcarenites of Callovian Jurassic horsts. Jurassic formations, but which is absent on Huayacocotla and the overlying Upper Jurassic series, which measures ~500 m in grabens, where it is in transitional contact with the underlying Huayacocotla and the overlying Upper Jurassic formations, but which is absent on Jurassic horsts.

A transgressive series (Fig. 2e) is initiated by the Tepéxic Formation (calcarenites of Callovian age; Erben, 1956) and continues upslope concurrently with the pelagic Santiago (Callovian-Oxfordian), Tamán (Kimmeridgian-Tithonian), Pimienta (Tithonian-Berriasian), Chapulhuacán, Ahuacaatlán, and Agua Nueva (Turonian) formations, which are composed of micritic limestone and shale. For the stratigraphy of this sequence, the reader is referred to Bodenlos (1956), Cantú (1971), and Carrillo-Bravo (1971).

A clastic series (Fig. 2e) is initiated by the Coniacian to middle Campanian San Felipe Formation. Pelagic limestone, platform-derived carbonate exoclasts, shale, sandstones, and graywackes of a wide compositional range characterize this formation. The sandstone and graywacke components were probably transported by contour currents along the VSP platform margin and not across the platform, because the Soyatal Formation, overlying the platform carbonates, does not contain any sandstones or graywackes. Far-ranging transport of these rocks by contour currents is indicated by their occurrence in the oil fields of southeastern Mexico (Santiago-Acevedo, 1980). The San Felipe beds are concordantly overlain by the Méndez Formation of Campanian to Maastrichtian age.

In the Tampico-Misanta foredeep, rhythmical, graded sandstone-shale flysch sequences of the Velasco and Chicontepec Formations (Busch and Gavela, 1978) accumulated in the late Maastrichtian(? to early Eocene. Thick- and medium-bedded sandstones are common in the traverse area (Tamazunchale-Huichihuayán, Fig. 1) and are interpreted as outer-fan or fan-fringe deposits by Bitter (1986). Paleocurrents, measured in the lobe deposits along the western margin of the Tampico-Misanta basin, were east directed but turned distally to the southeast, becoming parallel to the basin axis (Bitter, 1986). Most sandstones of the Chicontepec Formation are calichites that have an average composition of Q18F11R71, 59% of the rock fragments being limestone (Bitter, 1986). The paleocurrent direction of the lobe deposits and the rock composition indicate that the major source of sediment was the Jurassic and Cretaceous limestones of the Sierra Madre Oriental that were deposited in small fans at the basin margin.

**CORDILLERAN STRUCTURE**

**West of the Valles–San Luis Potosí Carbonate Platform**

The sedimentary column which crops out west of the VSP platform (Figs. 2a, 2b, and 2c) consists of three lithotectonic units. Two incompetent layers (Las Trancas–Soyatal Formations) sandwich a competent layer of variable thickness and lithology (Tamaulipas and El Doctor Formations).

The El Chilar anticline (Segerstrom, 1961) lies in the transition zone between the Mesa Central and Sierra Madre Oriental physiographic provinces. It is the most westerly Cordilleran structure of this area which has a continuous outcrop. The anticline is characterized by a 15° to 30° southwesterly dipping limb, which preserves a normal sequence of Las Trancas–Tamaulipas–Soyatal Formations (Figs. 3 and 5), and by a nearly flat crest which has some minor internal folds. It is limited on the northeast not by a limb, but by the northeast-directed Higue-rillas thrust fault (Carrillo-Martínez and Suter, 1982), which brings Tamaulipas beds and the uppermost beds of the Las Trancas Formation into tectonic contact with the Soyatal Formation. The thrust fault is subhorizontal in the transverse exposure east of San Juan de la Rosa (Fig. 3), where horizontal separation along the fault perpendicular to strike amounts to >1,100 m. The El Chilar anticline does not seem to be caused by buckling above a basal décollement but rather by transport of the Higue-rillas thrust plate over a nonplanar fault surface (fault-bend fold; Suppe, 1983). In the construction in Figure 5, it was assumed that as a tectonic ramp which has the same dip as does the western flank of the anticline connects the exposed fault segment with a subhorizontal sole fault. The position of the sole fault was located by analogy with the better constrained El Doctor thrust nappe to the east. Given the constraints of the construction in Figure 5, the horizontal cross-sectional component of displacement along the Higue-rillas thrust fault is ~10 km for the base of the El Doctor Formation. The footwall of the Higue-rillas thrust is the north-trending San Lorenzo syn-
cline (Segerstrom, 1961). The depth of the San Lorenzo syncline is unknown, and its internal geometry is difficult to quantify, as only contorted Soyatal beds crop out.

The El Doctor thrust nappe (Figs 1 and 4) is bounded by the San Lorenzo and Maconi synclines (Fig. 5). In the walls of Mocetzuma Canyon, the thrust fault has an average dip of 24° west (Fig. 5) and a minimum horizontal displacement component of 2,800 m perpendicular to strike. The thrust sheet is frontally rotated around the axis marked on Figure 3, which may be the result of frictional drag, of a change in inclination of the thrust fault, or of the rupture of a pre-existing fold. No other important folds are known in the hanging wall.

There are two assumptions for extrapolation of the structure down to basement (Fig. 5). (1) An altitude of 800 m (with respect to present sea level) for the top of the El Doctor Formation in cases in which it is unaffected by local Cordilleran structural relief is deduced from the lowestmost outcrops of the Soyatal Formation in the interior of the VSP platform (footwall of Agua Fría thrust near Santo Domingo, Fig. 3). Regional isostatic uplift may be responsible for the high altitude of these marine sediments. (2) A depositional relief of 1,000 m, between the carbonate bank and the Zimapán basin is assumed. By using these levels and extrapolating the exposed dip of the thrust fault, a linear shortening, \( \Delta x \), of 5,550 m and an areal shortening, \( \Delta A \), of 2.51863 \( \times 10^7 \) m\(^2\) were determined for the top of the El Doctor Formation as the reference horizon (Fig. 5). The areal shortening, \( \Delta A \), is defined as the area between the deformed and undeformed configurations of a reference horizon. The two shortening parameters allow estimation of the distance, \( z = \Delta A/\Delta x \), between the reference horizon and the basal detachment zone (Laubscher, 1965, 1977; Dahlstrom, 1969; Hossack, 1979). If we neglect volume-loss strain (solution loss in the carbonates, tectonic compaction in the shales) and axial strain and if we assume that no material was transported along a fault other than the sole fault into or out of our section segment, \( z \) equals 4,580 m, which corresponds to a sole-fault depth of 3,780 m below present sea level (Fig. 5). This geometry is confirmed by the approximate parallelism between the thrust fault and the western flank of the structure and by the merger of the ramp with the detachment fault at the hinge between the western flank and the San Lorenzo syncline (Fig. 5). Imbrication of the El Doctor thrust would increase the linear shortening and make the detachment shallower.

If we use the top of the Las Trancas Formation as a reference horizon and assume a thickness of 1,800 m for the El Doctor Formation, the same linear shortening, \( \Delta x \), of 5,550 m and an areal shortening, \( \Delta A \), of 1.43138 \( \times 10^7 \) m\(^2\) results. This is 0.09485 \( \times 10^7 \) m\(^2\) short of the area needed to balance the section. The section could be balanced if we add that value difference of area to the system by steepening the thrust-fault inclination in the lower part of the section from 24° to 33°. The area deficiency could also be resolved by 450 m of layer-parallel slip of the El Doctor Formation on the Las Trancas Formation into the system or by cross-sectional dilatation in the Las Trancas Formation of 6.2%.

The El Piñón anticlinorium (Figs. 1 and 6), which is 11,000 m, is bounded by the Maconi and Aguacate synclines (Fig. 5). The structural relief between the crest of the anticlinorium and the Maconi syncline measures >1,800 m. The limbs and the crest of the anticlinorium are characterized by second-order folds (Fig. 5), the geometry of which is well traced by the morphological contrast between the Soyatal and Tamaulipas and between the Tamaulipas and Las Trancas Formations. The amplitudes of these second-order folds measure between 200 and 800 m. The folds of the southwestern limb are recumbent. The uppermost one is cut by a subhorizontal thrust fault, the direction of which is opposite to the regional southwestip dip direction of thrust faults (Fig. 5) and the age of which postdates the rotation of the southwestern flank of the anticlinorium. The folds of the crest and of the northeastern limb, on the other hand, have subvertical axial surfaces. The exposed linear shortening of the over-all structure is 6,000 m or 35%.

The Aguacate syncline is between the El Piñón anticlinorium and the Bonanza anticline. Its southwestern limb is slightly overturned, whereas the northeastern limb has a dip of 60° to 70°. The structure is elevated in comparison with the Maconi and El Fraile synclines, which can be explained by its transport along the El Volantín thrust fault (Fig. 5).

The Bonanza fold nappe is of regional extent; its core is eroded down to the Las Trancas Formation over a length of >80 km (Segerstrom, 1961, 1962). The structure is strongly overturned, is nearly recumbent, and is thrust to the northeast onto the El Fraile syncline along the El Volantín thrust fault (Fig. 5). Structural relief of the crest is 1,800 m with respect to the Aguacate syncline. The southwestern limb dips 60° to 70°, and the overturned limb dips 23° to the southwest. Thickness of the latter is tectonically attenuated in the Tamaulipas Formation, which is intensely chevron folded. The chevron folds are partly cut along the underlying El Volantín thrust fault (Fig. 7), which forms the contact between the Tamaulipas and Soyatal Formations (Fig. 3). The overturned geometry of the fold nappe and the intense deformation of the eastern limb (Fig. 5) can be explained by simple shear of the structure (Ramsay and others, 1983). The exposure and volumetric shortening component of the Bonanza fold nappe is 6,300 m. A translational shortening component exists (El Volantín thrust fault) but cannot be quantified using surface data.

The El Volantín thrust fault follows the western margin of the VSP carbonate platform but extends, farther southeast, into the Zimapán basin (Fig. 3). The fault dips 23° to the southwest and parallels the underlying stratigraphic contact between the El Abra and Soyatal Formations (Figs. 5 and 7). This configuration can be explained by rotation (≈23°) of the thrust fault and the upper and the lower plates due to their piggy-back transport over the Jiliapan thrust fault and formation of the fold east of the Jiliapan thrust fault (Fig. 5). This would suggest a west-to-east deformational sequence, as can be deduced at other places (series of thrust sheets on the eastern margin of the VSP platform, border thrust west of Tamazunchale). It could also be explained by depositional dip (≈23°) of the lower plate (foreslope of the VSP platform) and the development of the El Volantín thrust along this inclined pre-existing anisotropy. Geopetal fabrics could be used to distinguish the depositional from the structural dip component.

Balancing the section between the Maconi and El Fraile synclines (Fig. 5) using the top of the Las Trancas Formation resulted in a linear shortening, \( \Delta x \), of 21,100 m or 67%; 9,250 m of the linear shortening corresponds to the El Piñón anticlinorium (relative shortening: 48%), and 11,850 m, to the Bonanza fold/El Volantín thrust (relative shortening: 96%). The areal shortening, \( \Delta A \) (area between the initial and folded positions of the reference bed), for the same reference horizon is 3.8025 \( \times 10^7 \) m\(^2\), and the corresponding depth to décollement is \( z = \Delta A/\Delta x = 3,600 \) m, or 2,800 m below the present sea level (Fig. 5). The sole fault is deeper if volume-loss strain occurred. A 2.4° dip of the sole fault toward the internal part of the belt resulted from these area-balance considerations between the lower tips of the El Doctor and El Volantín thrust faults. This value and the direction toward the hinterland compare well with data from other fold-thrust belts (for example, Chapelle, 1978; Suter, 1981; Davis and others, 1983). The Jiliapan thrust fault trends, as does the El Volantín thrust, slightly oblique to the western edge of the VSP platform. The thrust fault is best developed where it coincides with the platform margin (Fig. 5, section BB'). The shortening diminishes where the thrust enters the platform farther north (Fig. 5, section AA'). Its shortening...
Figure 5. Structural section across the study area. The section part documented by surface data reaches a depth of 100 to 200 m above sea level east of the Valles–San Luis Potosí platform, 900 to 1,200 m between the Valles–San Luis Potosí and El Doctor platforms, and ~2,000 m west of the El Doctor bank. The subsurface part of the section is speculative but area balanced. Exposed part of AA' after Carrillo-Martínez and Suter (1982). The trace is marked in Figure 3 and the ages of the units are given in Figure 2. Explanations in the text.
slivers of El Abra composition occur in the Soyatal Formation, and the uppermost El Abra beds are in places tectonically truncated. A younger-on-older thrust below the Jiliapan thrust along the El Abra/Soyatal contact is also likely near Highway 85 (Fig. 9). The Jiliapan thrust fault, as is the El Volantín thrust fault, is parallel to bedding but dips 27° to the southwest. The thrust fault was probably initially horizontal and was rotated during the formation of the fold to the east (Figs. 3 and 5) and in connection with decoupling along a lower, incompetent layer.

Displacement along the Jiliapan thrust fault is at least 2,200 m in the outcrop shown in Figure 8. The effective shortening is probably much greater, as the platform edge and foreslope facies are not exposed (eroded part of upper plate or subsurface part of lower plate). El Abra beds that crop out contain miliolid limestone and intraformational pebbles that have black algal coatings, typical of tidal flats. Two facies belts, which together are 2,000 to 4,000 m wide, are thus missing. The minimum shortening along
the Jiliapan thrust fault, for geometric and stratigraphic reasons, therefore, is between 4,000 and 6,000 m (Fig. 5).

Valles–San Luis Potosí Platform

The Cordilleran structures on the VSP platform are difficult to quantify for the following reasons. (1) The base of the El Abra Formation does not crop out. (2) The contact between the El Abra and Soyatal Formations is not preserved in many places. (3) No marker horizons exist within the 1,500- to 2,000-m-thick El Abra Formation. (4) Structures are masked by karst morphology and in many cases, by caliche deposits; fresh outcrops exist only in canyons. The strata in many places are nearly horizontal, but in other places, such as the river valley between La Palma and Santo Domingo (Fig. 3), narrowly spaced, partly overturned folds that have hectometric amplitudes can be observed. Décollement may have therefore not only occurred in the underlying Pimienta and Las Trancas Formations but also in the evaporites of the platform interior (Guaxcamá Formation). Shortening inside the platform is difficult to estimate; the rotational shortening component displayed in Figure 5 measures only 750 m.

The platform, which in the study area is only 35 km wide, is broken in the middle by the Agua Fría thrust fault (Figs. 1 and 3), the front of which is well exposed along the Jacala–Santo Domingo and Cardonal–San Andrés Miraflores roads, where El Abra Formation is thrust over Méndez beds. The frontal part of the thrust slab is unfolded in the section line but is commonly more folded than in our section, especially west of Santo Domingo.

Area balancing of the hanging wall of the Agua Fría thrust (western part of section BB’ in Fig. 5) resulted in a linear shortening of 6,400 m. Areal shortening (reference horizon: top of the Las Trancas Formation) measures $1.01025 \times 10^7$ m$^2$, and the depth to décollement calculated from shortening is 1,580 m, which corresponds to a depth of 2,580 m below sea level. This is in good agreement with the depth of the decoupling horizon calculated for the structures farther west. The modeled inclination of the sole fault between the lower tips of the El Volantín and Agua Fría thrust faults (horizontal distance: 16,150 m; vertical distance: 220 m) is 0.8° toward the hinterland.

The subsurface structure as modeled in Figure 5 is probably not far from that of reality, given...
Figure 8. Jiliapan thrust north of Puerto de las Trancas, western edge of Valles–San Luis Potosí platform. View to the west-northwest, showing true cross section. 1 = upper plate (Tamaulipas Formation). 2 = thrust fault. 3 = Soyatal Formation, and 4 = El Abra Formation of the lower plate. 5 = El Fraile syncline (Tamaulipas Formation).

Figure 9. Jiliapan thrust near Highway 85. View to the south, showing true cross section. 1 = upper plate (Tamaulipas Formation). 2 = thrust fault. 3 = Soyatal Formation, and 4 = El Abra Formation of the lower plate. 5 = Highway 85. On the right, the subhorizontal uppermost beds of the El Abra Formation are sheared parallel to the major fault.

the simple structural geometry at the surface. It has been assumed in the construction of the subsurface geometry that rotation is limited to the upper plate. If the axial planes shown in Figure 5 reach to the sole fault, then the section would look somewhat different, due to the folding of the thrust fault and the lower plate. Another possibility is that the thrust fault has a staircase geometry with flats beneath the cores of the two anticlines and ramps below their western flanks.

Western Edge of the Valles–San Luis Potosí Platform

Deformation along the western edge of the VSP carbonate platform is marked by thrust faults (Fig. 3) that have a slightly oblique trend to the bank margin where they are crossed by section BB' (Fig. 3). Their surface geometry has been described in Suter (1984).

The Lobo-Ciénega thrust fault contains a near-surface layer-parallel segment similar to those in the El Volantín and Jiliapan thrust faults and the nearby Xilitla thrust fault (Fig. 1). This detachment in the mechanically incompetent Upper Cretaceous Soyatal Formation is exposed somewhat north of our section, along Highway 120 (Fig. 3) for a length of 3,500 m. The exposed Lower Cretaceous carbonates of the platform-basin transition zone are cut at an angle <20° by the Lobo-Ciénega and Agua Zarca thrust faults (Fig. 5). The foreslope deposits (Tamabra Formation) are missing immediately north of the Moctezuma River. They are very probably in the subsurface, in the lower plate of the Lobo-Ciénega thrust (Fig. 5). A third major thrust fault (Misión thrust, Figs. 1 and 3) crops out farther south but has zero or near-zero shortening where it is crossed by section BB' (Fig. 5). The Agua Zarca and Misión thrust surfaces may be diverging splays (Boyer and Elliott, 1982) of the Lobo-Ciénega thrust fault, but the junctions are not defined; the junction between the Lobo-Ciénega and Agua Zarca thrust faults would lie close to Highway 120. If the Agua Zarca thrust fault is a divergent splay of the Lobo-Ciénega thrust fault, then the structure composed by the two faults is probably a duplex, the roof thrust being in the Soyatal Formation and the floor thrust being the basal detachment (Fig. 5).

The modeled linear shortening (Fig. 5) is 7,800 m along the Lobo-Ciénega thrust fault and 2,400 m along the Agua Zarca thrust fault (reference horizon: top of the Pimienta Formation). The areal shortening for the same reference horizon is \(1.36988 \times 10^7\) m\(^2\) for the section segment delimited by the Agua Fría and Agua Zarca thrust faults. The corresponding depth to detachment is 2,350 m below sea level. This value is comparable to the depth to décollement obtained for the segment between the Jiliapan and Agua Fría thrust faults farther west (~2,580 m). These data suggest, as in the western part of our traverse, a slight inclination (<2°) of the basement toward the internal part of the belt. Passive rotation of the Lobo-Ciénega and Agua Zarca thrust sheets can be explained by subsequent upward ramping along a lower, unexposed thrust fault (Fig. 5), which implies an emplacement from southwest to northeast.
East of the Valles–San Luis Potosí Platform

The sedimentary column between the VSP carbonate platform and the leading edge of the Cordilleran orogenic belt is composed of layers that have contrasting mechanical competencies. Folding seems to have been controlled by a thick red-bed sequence (Cahuasas Formation), which forms gentle buckles in outcrops of the Amajac Canyon south of our section, but disharmonic folding occurred on several superjacent weak layers.

The oldest lithologic unit exposed in the traverse along the Moctezuma Canyon is the Tepéixico Formation. The section (Fig. 5) is characterized by mostly upright, open to closed flexural-slip folds. The Tamán Formation buckled as an isolated competent layer (second-order folds) because of its position between the highly incompetent Santiago and Pimienta Formations. The rocks above the Pimienta beds buckled as a whole, as they form a stack of well-bedded competent layers (only the lowermost of them, the Chapulhuacán Formation, is completely traced on Fig. 5) which lacks thicker internal incompetent layers. The rocks above the Pimienta beds conform in places to the shape of the folds existing in the Tamán Formation. At other places, disharmonic (third-order) folds developed (Fig. 5) due to the discrete surfaces of low cohesion between the Chapulhuacán and the Pimienta and between the Pimienta and Tamán Formations. The Pimienta beds were, in the latter case, thinned in the limbs from whence the material flowed into the fold cores, which resulted in a wide range of thicknesses from 150 to 750 m for this formation. This decoupling of the series above the Pimienta Formation caused the bulk shortening of the Chapulhuacán Formation to be greater than that of the Tamán Formation, which implies layer-parallel transport of the series above the Tamán Formation on the Pimienta Formation into this section segment.

The frontal thrust (first mentioned by Heim, 1926, 1940) is easily traceable on the northern wall of the Moctezuma Valley west of Tama-zunchale. The thrust fault is crossed by Federal Highway 85, 2,500 m west of the bridge over the Moctezuma River (tectonic contact of the Chapulhuacán Formation with San Felipe beds), from where it ascends at 15° to 25° dip (but parallel to bedding) for ~350 m and, farther east, shows a gradient toward the east (Fig. 5). The thrust fault must have been deformed by the formation of the underlying fold, in the core of which the Ahuacatlán Formation crops out in the Moctezuma Valley (Fig. 3). The minimum displacement along the border thrust can be estimated for the Pimienta-Chapulhuacán contact by adding the measurable horizontal displacement component (1,600 m) to the shortening which is caused by an assumed 30° shearing of the unexposed part of the lower plate (Fig. 5) down to the reference horizon (350 m).

The minimum linear shortening is 3,550 m or 23% for the Huayacocota anticlinorium (1,600 m rotational component and 1,950 m translational component due to the frontal thrust) and 1,450 m or 6.4% for the Pisafloros anticlinorium, with reference to the Pimienta/Chapulhuacán contact (Fig. 5). This is a minimum value, because the rocks show an additional shortening by means of metre-sized chevron-type folds.

If we assume, as we did farther west, a stratigraphic depth of ~1,000 m for the top of the Upper Jurassic, then we get an areal shortening of 5.5860 × 107 m2 for the segment between the Agua Zarcá and the border thrusts for this reference horizon (top of the Pimienta Formation).

Surprisingly, the resulting depth of the detachment fault (12,172 m below sea level) is totally inconsistent with the depth of the base of the sedimentary sequence in the Maguey-2A well (Fig. 1) east of the Huayacocota anticlinorium (−2,664 m; López-Ramos, 1972) and with the depth to detachment calculated for the fold-thrust belt farther west. This discrepancy may be due to the following.

(1) Horizontal shortening of the basement (thick-skinned deformation) with intrabasement decoupling at a depth of ~12 km, similar to the basement-cored Huizachal-Peregrina anticlinorium (Heim, 1940; Carrillo-Bravo, 1961; de Cserna and others, 1977; Ortega, 1978) farther north, west of Ciudad Victoria.

(2) Thin-skinned deformation, but assuming a much higher depositional level of the Upper Jurassic. Such a Jurassic high would laterally extend from the western limb of the Pisafloros anticlinorium in the west to the segment of the border thrust which crops out in the east (Fig. 5). An upper limit for the depositional level of the Pimienta top on this Jurassic high is its present altitude in the Xilitla-Chapulhuacán syncline (Fig. 5) of 100 m above sea level. For this depositional level, the areal shortening of the segment between the Agua Zarcá and border thrust faults reduces to 1.9925 × 107 m2 and z to 3,885 m below sea level. A sole fault in this depth could coincide with the base of the sedimentary sequence. This interpretation would imply more sedimentation in this area than farther west during the Triassic and Early/Middle Jurassic and a basin inversion in the Late Jurassic.

(3) Thin-skinned deformation with a large layer-parallel segment of the border thrust in the Upper Cretaceous, which reduces the areal shortening and augments the linear shortening. Figure 5 shows an area-balanced attempt to model this scenario. Assumptions are a depositional level of ~1,000 m for the top of the Pimienta Formation, a layer-parallel fault segment at −500 m in the San Felipe Formation, and a tectonic ramp in the west which has a dip of 24° (which corresponds to the dip of the western limb of the Pisafloros anticlinorium). The resulting linear shortening is 28.52 km for the layer-parallel fault segment and 31.57 km for the entire section east of the VSP platform. The border thrust would splay near Tama-zunchale and have a branch following the mountain front (Fig. 3) and a blind branch extending layer-parallel into the Tampico-Misantla basin (Fig. 5) associated with disharmonic detachment folding in the overlying flysch. This interpretation, however, cannot be confirmed from the stratigraphically deeper outcrops in the Amajac and Claro Canyons (Fig. 3).

North of the Main Traverse

Two deep wells exist somewhat north of the eastern part of the traverse area. Maguey-2A is in the foreland, 23 km east-southeast of Huichihuayán, and Valle de Guadalupe-1 is in the interior of the VSP platform (Fig. 1). Given the uncertainties of our subsurface extrapolations for the Pisafloros and Huayacocota anticlinorium shown in Figure 5, I used data from these two wells in the construction of an area-balanced cross section down to décollement (Fig. 11) in order to constrain both the subsurface geometry and estimates of the shortening. Depth and minimum inclination of the basement surface are constrained by the lower limit of the incompetent Huayacocota Formation in the Maguey-2A well (−2,664 m, overlying metamorphic basement) and by the bottom depth of the Valle de Guadalupe-1 well (−2,750 m) in the Tamán Formation (Upper Jurassic). Given the horizontal distance between the two wells (46.0 km), an inclination of ≥0.1° toward the interior of the belt results for the basement surface (dashed line on Fig. 10).

Balance of the Segment Between Maguey-2A and the Lower Plate of the Xilitla Thrust. For the base of the Agua Nueva Formation (base of the Upper Cretaceous) as reference horizon, a linear shortening of 2,180 m and an areal shortening of 4.204 × 107 m2 results (Fig. 13a) if we assume that the lower plate of the Xilitla thrust maintains the outcrop dip of 10° down to the point of its stratigraphic depth. Dividing the area by the linear shortening, we should get the distance between the detachment fault and the stratigraphic level of the reference
linear shortening is required, for example, in the form of an unexposed bedding-plane thrust as modeled in Figure 11. The inconsistency of the calculated linear shortening with detachment at the base of the sedimentary sequence can be somewhat modified if we assume deliberately a steeper (40°) dipping lower plate for the Xilitla thrust (Fig. 10b). Additionally, we can model the flexure which crops out in the flysch west of Axtla as a drape fold (Fig. 10b) and an associated normal fault below the flysch. The assumed structural configuration could be explained by subsidence of the flysch-filled foredeep. This reduces the areal shortening drastically (now \(2.049 \times 10^7\) m²; new linear shortening: 1,930 m) but without changing essentially our former result of an apparent intrabasement depth of the sole fault.

If the deformation is thin skinned as shown in Figure 1, and if the sole fault has approximately the depth inferred from well data, then there must be a linear shortening of -20 km, most of it being limited to the subsurface in the form of a bedding-plane thrust ("blind" thrust). Displacement along the blind thrust must be balanced in the flysch of the overlying sequence by disharmonic detachment folding farther east, in the Tampico-Misantla basin. In the Huayacocotla anticline, folding of this thrust fault is suggested by the depth of convergence of the axial planes (Fig. 11).

**Segment Between Valle de Guadalupe-I and the Xilitla Thrust Fault.** The other segment shown in Figure 11 is not material balanced, as no pinline can be defined west of the section segment, that is, the system is open in the west. Valle de Guadalupe-I is situated in a doubly plunging fold which has a length of 14 km. The top of the Pimienta Formation was cut in Valle de Guadalupe-I at a depth of -906 m but at -2,137 m in Maguey-2A; the vertical offset is comparable to the throw of the Xilitla thrust (1,050 m; Suter, 1984). This suggests that the Xilitla thrust reaches the sole fault west of Valle de Guadalupe-I (Fig. 11). The thickness of the El Abra Formation cut in Valle de Guadalupe-I, added to the thickness which crops out above the well site, gives a value nearly double the stratigraphic thickness. This can be the result of tectonic repetition caused by the Lobo-Ciénega thrust (Fig. 11).

It can be concluded that the deformation of the Pisaflores and Huayacocotla anticlinoria either involves horizontal shortening of the basement (thick skinned) with intrabasement decoupling in a depth of 10 to 20 km, or if thin skinned, probably is associated with much more shortening than expected given surface data. Seismic and magnetic data are needed to specify further the structural subsurface geometry.

**DEFORMATION MECHANISMS**

The deformation mechanisms vary along our section. Deformations are brittle in the limestones of the eastern part, east of the VSP platform (oblique and layer-parallel discrete shear zones and subordinated occurrence of tectonic stylolites), whereas the mudstones of the eastern part (Huayacocotla and Santiago Formations, Huayacocotla and Pisaflores anticlinoria) exhibit a spaced cleavage at high angles to bedding, developed by pressure solution. The deformations are of the brittle-ductile transition type in the western part between the El Doctor and VSP platforms (Carrillo-Martínez and Suter, 1982) and are morphologically characterized by flow folds and axial-plane cleavage in limestone, *en echelon* shear zones instead of shear fractures, mylonitic limestone around shear lenses and along thrust faults, strained ammonites (Las Trancas Formation), and very low-grade metamorphism (?) in the shales in the cores of the Maconi, El Piñón, and Bonanza folds. The amount of strain and the deformation-causing mechanisms in the rocks of the western part remain to be studied. The ductility of rocks in the western part of the traverse, notwithstanding the apparent low overburden of 45 to 50 MPa for the lower-
er rocks, can be due to various reasons. (1) Additional lithostatic load could result from the prior existence of tectonic units, now eroded, above the observed structures (tectonic burial), for which, however, there is no additional evidence. (2) Elevated regional isotherms and high heat flow, probably caused by several large intrusives exposed in the western part of the traverse (Fig. 3), could put the brittle-ductile transition zone up to lower confining pressures and facilitate greater shortening. These plutons, which form part of a magmatic arc (Clark and others, 1982), intrude the documented Cordilleran structures, but their isotopic ages (Kiyokawa, 1981) are not much younger than the interval obtained by bracketing the deformation along the eastern edge of the VSP platform (62.2 to 68 Ma; Suter, 1984). A similar relation between a thermal peak, caused by a migrating magmatic arc, and relatively great ductility (compared with more external structures) is reported from the North American Cordillera farther north by Armstrong (1974) and by Burchfiel and Davis (1975).

CONCLUSIONS

The Sierra Madre Oriental in east-central Mexico shows structural elements typical of a fold-thrust belt. The style of deformation is controlled mainly by the geometry and lithology of two major Cretaceous carbonate banks, El Doctor and Valles–San Luis Potosi, the long dimensions of which parallel the Cordilleran structural trend.

The interiors of the two ~1,500- to 2,000-m-thick carbonate platforms remain relatively undeformed, with the exception of the very probably thin-skinned Agua Fría thrust which has a modeled shortening of 6.4 km.

Shortening on the margins of the two platforms measures ~5 km for the eastern edge of the El Doctor bank (El Doctor fault nappe), 12 km for the western edge of the Valles–San Luis Potosi platform (Bonanza fold nappe), and 10 to 12 km for the eastern edge of the Valles–San Luis Potosi platform (series of imbricates) and is very probably thin skinned. The observed thrust faults that cut across the platform-edge carbonates are ~20°-inclined tectonic ramps that were partly steepened by imbrication or by subsequent folding but pass in the overlying, mechanically weak Upper Cretaceous rocks nearly parallel to bedding. The shear instability of the eastern platform edges can be explained by the change of thickness across the platform-basin transition zone, which leads to a stress concentration if an external load is applied in the west. The western edge of the Valles–San Luis Potosi platform, which has a depositional foreslope dip of probably 20° to 25° west (Tamabra/Soyatal contact), formed a pre-existing discontinuity inside the sedimentary package which had a favorable orientation for its activation as a shear fault. Initial failure of the El Volantín and Jiliapan thrust faults probably occurred at the Soyatal/Tamabra contact at a place where the foreslope was perpendicular to the maximum principal stress trajectories. From there, the thrust-fault surfaces propagated down to the sole fault, upward to the surface, and along strike. The thrust’s displacements decrease where the...
faults pass along strike into platform-interior or basin facies.

The area between the two platforms (Zimapán basin) is characterized by very probably thin-skinned low-angle thrust faults and décollement folds and partly by ductile shear. The distance between the two platforms must have measured ~48 km before deformation and was reduced to 27 km (shortening of 21 km or 44%). The thick, homogeneous platform assemblages acted as pistons that pressed the material between them not only upward but also relatively toward the two platforms. This is indicated by the axial planes of the structures between the platforms, which form a fan. They are vertical in the middle but show a vergence toward the two platforms for the rest of the area (western limb of the El Piñón anticlinorium toward the El Doctor bank, Bonanza anticline toward the Valles–San Luis Potosí platform, Fig. 5).

The area between the Valles–San Luis Potosí platform and the foreland is lithologically marked by a well-layered package which became deformed by predominantly upright, open to closed flexural-slip folds and, to a lesser extent, by overthrusts. Its exposed shortening (Pisaflores and Huayacocotla anticlinoria) measures 5,000 m or 14.2%. A discrepancy exists between the observed linear shortening and the much larger modeled areal shortening. It can be explained by thin-skinned deformation with a near-surface blind thrust of 20 to 30 km of shortening, which extends into the Tampico-Misantla foredeep, or by intrabasement decoupling in a depth of 10 to 20 km.

The calculated shortening for the entire traverse amounts to a minimal 41,400 m or 24.9% (unextrapolated section) and a maximal 90,070 m or 40.3% (area-balanced section). The relative shortening is of a magnitude typical of foreland fold-thrust belts. In a structural cross section through the outermost part of the Jura Mountains, for example, an over-all linear shortening of 28% was measured (Suter, 1981). If a relative shortening of 25% is assumed for the entire area between the foreland and the present location of the convergent boundary between the Cocos and North American plates, we get an absolute shortening of 200 km for Cordilleran deformation of central Mexico. Deformation of central and western Mexico, however, is hidden below young basin fill of the Mesa Central and below ignimbrite sheets of the Sierra Madre Occidental and can hardly be constrained; the westward extension of the fold-thrust belt is unknown. The shortening amount is compatible, however, with the shortening calculated for the Cordilleran foreland fold-thrust belt farther north (Royse and others, 1975; Price, 1981; Mountjoy and others, 1984).

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