Evidence for two Cretaceous superposed orogenic belts in central Mexico based on paleontologic and K-Ar geochronologic data from the Sierra de los Cuarzos

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ABSTRACT

The continental interior of Mexico is characterized by a Late Cretaceous–Eocene fold-thrust belt named the Mexican Fold-Thrust Belt, which shows characteristics of an eastward-tapering orogenic wedge. The juxtaposition of the Guerrero terrane to the west of the Mexican Fold-Thrust Belt has motivated many to propose the accretion of this terrane as the cause for the regional shortening in the Mexican continental interior. The Sierra de los Cuarzos is located in the westernmost Mexican Fold-Thrust Belt, directly to the east of the boundary with the Guerrero terrane. Based on its position, the Sierra de los Cuarzos is key in reconstructing the possible propagation of shortening deformation from the Guerrero terrane suture belt into the Mexican continental interior. Our new paleontologic and K-Ar geochronologic data from the Sierra de los Cuarzos show that shortening in the westernmost Mexican Fold-Thrust Belt started ca. 83 Ma, which is ~30 m.y. later than the late Aptian age of the Guerrero terrane suture boundary. Therefore, the integration of our new paleontologic and geochronologic determinations with previous data suggests that the Guerrero terrane was already accreted and amalgamated with the Mexican continental interior at the time of the formation of the Mexican Fold-Thrust Belt. In light of this, the shortening structures in the western Mexican Fold-Thrust Belt do not show any in-sequence relationship with the adjacent Guerrero terrane suture belt. Therefore, we favor the idea that the Guerrero terrane suture boundary and the Mexican Fold-Thrust Belt are two distinct orogens that mark two distinct stages of tectonic evolution of the North American Pacific margin.

INTRODUCTION

After the break-up of Pangea, the Pacific margin of North America was involved in numerous different orogenic events (e.g., Sonoma, Sevier, Laramide) that were triggered by distinct tectonic processes related to prolonged subduction of the Farallon plate (e.g., Atwater, 1989; Bird, 1996; Dickinson and Lawton, 2001; Dickinson, 2009). These processes include accretion of juvenile terranes, variation in convergence rates, and changes in subduction directions, among others (Coney et al., 1980; Bird, 1998; Saleeby, 2003; English and Johnston, 2004; Liu et al., 2010). In central Mexico, recognizing the superposed effect of different tectonic processes is difficult because the timing, evolution, and origin of the shortening events that shaped the Pacific margin during Cretaceous and early Paleogene time are still a matter of debate. At present, two main geodynamic scenarios have been proposed for the Cretaceous–Eocene evolution of the Mexican Pacific margin. In scenario 1, the Pacific margin of Mexico is inferred to have undergone a major Late Cretaceous–Eocene shortening event caused by the collision and accretion of an allochthonous arc terrane named Guerrero terrane, which is currently exposed in the western half of Mexico (Figs. 1 and 2A; Coney et al., 1980; Campa and Coney, 1983; Mendoza and Suásteugi, 2000; Keppie, 2004; Talavera-Mendoza et al., 2007). According to this scenario, an accretionary event produced a suture belt along the eastern boundary of the Guerrero terrane, as well as subsequent eastward propagation of shortening within the continental interior, producing an ~300-km-wide fold-thrust belt named the Mexican Fold-Thrust Belt (MFTB) by Ortega-Gutiérrez et al. (1992) (Fig. 2A; Coney et al., 1980; Campa and Coney, 1983; Mendoza and Suásteugi, 2000; Keppie, 2004; Talavera-Mendoza et al., 2007). Alternatively, in scenario 2, accretion of the Guerrero terrane took place during the late Aptian, producing a relatively narrow suture boundary that was subsequently superposed by a late Cenomanian–Eocene orogenic belt, which extends for ~650 km from the present-day Mexican Pacific trench into the MFTB exposed in the continental interior (Fig. 2B; Chioldi et al., 1988; Quintero-Legorreta, 1992; Dickinson and Lawton, 2001; Nieto-Samaniego et al., 2007; Cuellar-Cardenas et al., 2012; Martini et al., 2012). According to this scenario, the late Aptian Guerrero terrane suture boundary and the late Cenomanian–Eocene fold-thrust belt are two distinct and superposed orogens that mark two different stages in the tectonic evolution of the North American Pacific margin (Chioldi et al., 1988; Quintero-Legorreta, 1992; Dickinson and Lawton, 2001; Nieto-Samaniego et al., 2007; Cuellar-Cardenas et al., 2012; Martini et al., 2012). While the late Aptian suture boundary has been univocally related by previous authors to the accretion of Guerrero terrane (e.g., Dickinson and Lawton, 2001; Martini et al., 2013), the cause for the late Cenomanian–Eocene fold-thrust belt is still under debate. Variation in convergence rates and changes in subduction directions along the Mexican Pacific trench, possibly accompanied by the gravitational collapse of the uplifting continental crust, have been postulated...
as the possible leading forces that produced the late Cenomanian–Eocene fold-thrust belt (Solari et al., 2007; Cuellar-Cardenas et al., 2012).

In this paper we test the two geodynamic scenarios along the Zihuatanejo-Guanajuato-Tamazunchale transect, which extends in south-central Mexico from the Guerrero terrane western margin to the exposed front of the MFTB in the Mexican continental interior (Fig. 1). This transect has been used in several stratigraphic, structural, and geochronological studies that constrain more exhaustively some aspects of the tectonostratigraphic evolution of the Guerrero terrane and MFTB than in other areas of Mexico (e.g., Suter, 1984; Carrillo-Martínez, 1989; Centeno-García et al., 2008; Martini and Ferrari, 2011; Martini et al., 2013; Fitz-Díaz et al., 2012; Omaña et al., 2013; Fitz-Díaz et al., 2014). We present new stratigraphic, paleontologic, and K-Ar geochronologic data from the Sierra de los Cuarzos, which is located in the westernmost part of the MFTB, 40 km to the east of the Guerrero terrane suture boundary exposed at Guanajuato (Fig. 1). Our data permit us to explore the controversy regarding the relationship between the accretion of the Guerrero terrane and the development of the MFTB in central Mexico, and thereby to improve our understanding on the tectonic processes that shaped the Pacific margin of southern North America during late Mesozoic time.

### GEOLOGIC BACKGROUND

#### Guerrero Terrane

Along the Zihuatanejo-Guanajuato-Tamazunchale transect, the Guerrero terrane is exposed between Zihuatanejo and Guanajuato (Fig. 1) and is composed of Late Jurassic–Early Cretaceous submarine arc and backarc assemblages that unconformably overlie a Late Triassic polydeformed metamorphic
basement named the Arteaga Complex (Fig. 3; Mendoza and Suástegui, 2000; Centeno-García et al., 2008; Martini et al., 2009, 2011). Some lines of evidence indicate that the Guerrero terrane represents a North American extensional arc that was rifted from nuclear Mexico during Tithonian–early Aptian backarc extension and subsequently accreted back to the Mexican continental interior, producing backarc inversion and the development of a fold-thrust suture belt exposed at Guanajuato (Martini et al., 2011, 2014). At Guanajuato, arc accretion and consequent development of the suture belt are bracketed to the late Aptian by paleontologic and U-Pb geochronologic ages (Chiodi et al., 1988; Martini et al., 2013) (Fig. 3). After accretion, Albian age reefal limestones of the La Perlita Formation were unconformably developed on the sheared and folded volcano-sedimentary assemblages exposed at Guanajuato (Chiodi et al., 1988; Quintero-Legorreta, 1992), whereas Albian–early Cenomanian age reefal and lagoonal limestones interbedded with volcanic rocks were conformably deposited on previous arc assemblages in the western part of the Guerrero terrane, between Zihuatanejo and Huetamo (Figs. 1 and 3; Mendoza and Suástegui, 2000; Centeno-García et al., 2008; Martini et al., 2008, 2009; Martini and Ferrari, 2011); Deposition of Albian–early Cenomanian age limestones was followed by a late Cenomanian, regional-scale shortening event in the western part of the Guerrero terrane, producing folding and uplift of the successions previously deposited between Zihuatanejo and Huetamo (Figs. 1 and 3; Centeno-García et al., 2008; Martini et al., 2009; Martini and Ferrari, 2011). Major thrust and folds have been also described in the Albian limestone of the La Perlita Formation at Guanajuato (Fig. 3; Chiodi et al., 1988; Quintero-Legorreta, 1992); however, the age of these shortening structures is broadly constrained to the Cenomanian–Eocene (Quintero-Legorreta, 1992) and a possible relationship with the late Cenomanian deformation in the Zihuatanejo-Huetamo area is difficult to establish. Shortening and uplift in the Zihuatanejo-Huetamo area were followed by the unconformable deposition of late Cenomanian-Maastrichtian, fluvial-alluvial successions (Centeno-García et al., 2008; Martini et al., 2009; Martini and Ferrari, 2011) (Figs. 1 and 3). These continental successions were dominantly derived from the underlying Albian–early Cenomanian limestone in their lower parts, and display a progressive increase in the contribution from arc-volcanic rocks toward the upper stratigraphic parts (Centeno-García et al., 2008; Martini and Ferrari, 2011).
The MFTB is an ~300-km-wide, eastward-tapering orogenic wedge exposed in the eastern half of the Zihuatanejo-Guanajuato-Tamazunchale transect, between Sierra de los Cuarzos and Tamazunchale (Figs. 1 and 4; Suter, 1987; Fitz-Díaz et al., 2012). Most of the rocks composing the MFTB along the selected transect are part of Late Jurassic–Cenomanian dominantly calcareous basins and platforms that were originally developed on Early–Middle Jurassic continental successions and pre-Jurassic metamorphic rocks (Fig. 3; Suter, 1987; Carrillo-Martínez, 1989; Fitz-Díaz et al., 2012, 2014). According to this interpretation,

**MFTB**

The MFTB is an ~300-km-wide, eastward-tapering orogenic wedge exposed in the eastern half of the Zihuatanejo-Guanajuato-Tamazunchale transect, between Sierra de los Cuarzos and Tamazunchale (Figs. 1 and 4; Suter, 1987; Fitz-Díaz et al., 2012). Most of the rocks composing the MFTB along the selected transect are part of Late Jurassic–Cenomanian dominantly calcareous basins and platforms that were originally developed on Early–Middle Jurassic continental successions and pre-Jurassic metamorphic rocks (Fig. 3; Suter, 1987; Carrillo-Martínez, 1989; Fitz-Díaz et al., 2012, 2014). The beginning of shortening in the MFTB has been considered to be marked by the deposition of the late Cenomanian–Santonian Soyatal Formation, which is composed of calcareous turbidites interbedded with pelagic limestone and shale (Hernández-Jáuregui, 1997; Fitz-Díaz et al., 2014). This unit is exposed in the western and central parts of the MFTB (Fig. 4), and has been interpreted as a foredeep clastic wedge that was derived from uplifted Late Jurassic–Cenomanian calcareous successions of the westernmost MFTB (Carrillo-Bravo, 1971; Hernández-Jáuregui, 1997; Fitz-Díaz et al., 2012, 2014). According to this interpretation,
the foraminiferal assemblage at the base of the Soyatal Formation constrains the onset of the shortening in the westernmost part of the MFTB between late Cenomanian and Turonian time (Fig. 3; Kiyokawa, 1981; Hernández-Jáuregui, 1997; Omaña et al., 2013). In the eastern part of the MFTB, between El Lobo and Tamazunchale (Fig. 4), foredeep deposits are represented by Campanian–Maastrichtian turbidites of the Méndez Formation (Suter, 1987; Fitz-Díaz et al., 2012), whereas foredeep turbidites of the Velasco and Chicontepec Formations are exposed east of Tamazunchale and were deposited between Paleocene and Eocene time (Figs. 3 and 4; Suter, 1984, 1987). The spatial and temporal distribution of foredeep deposits has motivated many to propose that shortening in the MFTB migrated progressively from west to east between the late Cenomanian and Eocene (Fig. 3; Fitz-Díaz and van der Pluijm, 2013, 2014). Such an eastward migration of the shortening is supported by available Ar-Ar and K-Ar ages on authigenic illite from thrusts and folds between Toliman and Tamazunchale. Geochronologic data document that shortening took place in the 83–75 Ma time interval between Toliman and San Joaquín, in the western part of the MFTB, ca. 64 Ma in the vicinity of El Lobo, and ca. 43 Ma to the east of Tamazunchale (Fig. 4; Fitz-Díaz and van der Pluijm, 2013; Fitz-Díaz et al., 2014; Garduño-Martínez et al., 2015).

The Sierra de los Cuarzos is located in the westernmost part of the MFTB, 40 km to the east of the Guerrero terrane suture boundary exposed at Guanajuato (Figs. 1 and 4). Based on its position, the Sierra de los Cuarzos is key in reconstructing the possible propagation of the shortening deformation from the Guerrero terrane suture boundary into the Mexican continental interior; therefore, we examined exposures of the Sierra de los Cuarzos to test the possible relationship between Guerrero terrane accretion and the shortening deformation in the MFTB. The Sierra de los Cuarzos contains exposures of a sheared and folded Mesozoic sedimentary succession that is unconformably overlain by Oligocene–Miocene volcanic rocks (Alaniz-Álvarez et al., 2001). The age of shortening in the Sierra de los Cuarzos is broadly constrained by stratigraphic data between Early Cretaceous and Oligocene time (Fig. 3; Palacios-García and Martini, 2014); therefore, a correlation with the shortening structures documented in the Guerrero terrane and MFTB is difficult to establish. The stratigraphic record exposed in the Sierra de los Cuarzos is composed of three informally
defined units that were deposited under different tectono-sedimentary conditions (Palacios-García and Martini, 2014). The oldest unit is the Sierra de los Cuarzos formation (Figs. 3 and 5), which is composed of Late Jurassic–Early Cretaceous siliciclastic and calcareous turbidites, slumps, and debris-flow deposits derived exclusively from sources in the Mexican continental interior (Palacios-García and Martini, 2014). The Sierra de los Cuarzos formation is overlain by the Pelones formation (Figs. 3 and 5), which consists of volcanioclastic turbidites, debris- and mud-flow deposits derived from a mix of sources that comprises the Guerrero terrane arc and backarc assemblages, as well as metamorphic successions exposed along the western margin of nuclear Mexico (Palacios-García and Martini, 2014). Based on its mixed provenance, the Pelones Formation has been interpreted as a syntectonic unit related to the collision and accretion of the Guerrero terrane to the Mexican continental interior (Fig. 3; Palacios-García and Martini, 2014). The age of the Pelones formation is currently not well constrained. However, the youngest zircons obtained from this unit define a maximum depositional age estimate of $127.8 \pm 0.8$ Ma (Palacios-García and Martini, 2014), which permits the interpretation of the Pelones formation as a syntectonic clastic wedge related to the late Aptian accretion of the Guerrero terrane. The Pelones formation is overlain by calcareous beds of the Españita formation (Figs. 3 and 5; Palacios-García and Martini, 2014). Considering its stratigraphic position above the Pelones formation, the depositional age of the Españita Formation is key in assessing the timing of the Guerrero terrane accretion, as well as of the subsequent shortening event that produced shearing and folding of the entire succession exposed in the Sierra de los Cuarzos. In spite of this, the age of the Españita Formation and the tectonic setting under which this unit was deposited has not been constrained.

### METHODOLOGY

We collected six samples of pelagic limestone from the Españita formation for paleontologic determinations, with the aim of constraining the maximum age of shortening deformation in the study area. Sample locations are given in Figure 5. In order to corroborate the maximum age of deformation based on paleontologic data, as well as to constrain the age of shortening in the Sierra de los Cuarzos in a numerical chronostratigraphic framework, we dated three concentrates of synkinematic white mica extracted from a kilometer-scale shear zone exposed at the base of the Españita formation (the Chupadero shear zone in Fig. 5) by the K-Ar method at the Laboratorio Nacional de Geoquímica of the Instituto de Geología, Universidad Nacional Autónoma de México (UNAM). We obtained muscovite concentrates using the methodology of Garduño-Martínez et al. (2015) that consists of (1) gentle disaggregation of rock samples using a porcelain crusher, (2) separation in distilled water according to Stoke’s law, and (3) centrifugation of mica flakes obtained by sedimentation in order to separate the $2–0.5 \mu m$ grain-size fraction. We selected the size fraction of $2–0.5 \mu m$ for isotopic analysis of the white mica concentrates in order to avoid possible contaminations with the sparse

![Figure 5. Detailed geologic map of the eastern part of the Sierra de los Cuarzos (after Palacios-García and Martini, 2014). A representative structural section and lower hemisphere stereographic projections representing the Chupadero shear zone are also shown. Locations of the samples used for paleontologic determination and K-Ar geochronology are shown on the map.](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/12/4/1257/3335761/1257.pdf)
detrital mica that is present in grain sizes >2 μm in the Sierra de los Cuarzos stratigraphic succession. The K-Ar methodology used is a modification of the classical technique, specifically designed to date small amounts of sample (50–100 mg), and was described in Solé and Enrique (2001) and Solé (2009). For potassium analysis we use X-ray fluorescence with high-dilution fused pearls to minimize both the amount of sample (50–100 mg) and the matrix effects (Solé and Enrique, 2001). For argon quantification, we used a CO2 laser system for sample fusion, followed by gas cleaning and measurement in a MM1200B noble gas mass spectrometer (Instituto de Geologia, UNAM). Age errors are reported at the 1σ level. The locations of the dated samples are shown in the geologic map of Figure 5, whereas samples coordinates and analytical data are given in Table 1.

### RESULTS

#### Field and Petrographic Observations

The Españita formation is exposed in the uppermost topographic parts of the Sierra de los Cuarzos (Fig. 5). It is composed of alternating, centimeter-to decimeter-thick beds of black limestone and shale, which are locally interbedded with centimeter-thick radiolarite strata. In most outcrops, limestone and radiolarite are boudinaged and pervasively to moderately recrystallized (Fig. 6A); however, in less deformed and recrystallized exposures, limestone and radiolarite preserve millimeter-scale laminations that suggest deposition by suspension settling through water. These finely laminated limestones are locally interbedded with a few decimeter-thick beds of sandstone with cross-lamination (Fig. 6B), which indicates that deposition by pelagic settling was occasionally interrupted by the emplacement of deposits formed by traction currents. Sandstones from these cross-bedded deposits are coarse to medium grained, moderately to poorly sorted, and are composed of fragments of bivalve shells and wackestone to packstone lithic grains. Due to pervasive to moderate recrystallization, sandstone samples collected are not suitable for paleontological determinations.

The base of the Españita formation is represented by the kilometer-scale, northwest-southeast–striking, gently northeast-dipping, brittle to ductile Chupadero shear zone, which developed along the contact with the underlying Pelones formation (Figs. 5 and 6C). The Chupadero shear zone is associated with an S1 foliation that is ubiquitously parallel to bedding planes (Fig. 6C). S1 is pervasive at the submillimeter scale in the first 2.5 m adjacent to the contact between the Pelones and Españita formations, and becomes progressively more widely spaced toward the shear zone boundaries. According to the classification of Twiss and Moores (1992), S1 is a disjunctive, rough to anastamosing foliation in sandstone and conglomerate layers of the Pelones formation, whereas in limestones of the Españita Formation S1 is a stylolitic foliation defined by oxides concentrations. Cleavage domains are defined by aligned white mica, fine-grained clay minerals, and minor chlorite. Microlithon domains contain muscovite fish and pressure shadows of fine-grained quartz. Mesoscopic and microscopic kinematic indicators observed on cuts parallel to the XZ plane of the finite-strain ellipsoid indicate a top-to-the-southwest direction of tectonic transport for the Chupadero shear zone (Figs. 6D, 6E). Considering that the Chupadero shear zone is ubiquitously parallel to bedding planes, we interpret this structure as a main detachment fault that was developed during a major shortening event as the result of the rheologic contrast that exists between the Pelones and Españita formations. This interpretation is in agreement with previous observations that documented the occurrence of other top-to-the-southwest, rheology-controlled detachment faults in the lower part of the Sierra de los Cuarzos stratigraphic record (Palacios-Garcia and Martini, 2014).

#### Paleontologic Determinations from the Españita Formation

We collected 6 samples of pelagic limestone from the Españita formation at a distance of 10–12 m from the Chupadero shear zone (Fig. 5). Samples are finely laminated wackestone-packstone, interbedded with radiolarian strata. The analyzed limestone samples contain abundant radiolarian tests and lesser amounts of planktic foraminifera. These latter have been identified as *Pseudoclavihedbergella amabilis* (Loeblich and Tappan), *Whiteinella brittonensis* (Loeblich and Tappan), *Whiteinella aprica* (Loeblich and Tappan), *Whiteinella paradubia* (Sigal), and *Muricohedbergella planispira* (Tappan) (Figs. 7A–7E). Whiteinellids found in the collected samples cover a wide stratigraphic range that spans from Cenomanian to Coniacian time (Fig. 7F; Premoli Silva and Verga, 2004). *Muricohedbergella planispira* has been typically assigned to the Alban–Turonian time interval (Fig. 7F; Loeblich and Tappan, 1961). *Pseudoclavihedbergella amabilis* was initially described in Cenomani stratana from the Eagle Ford Group in Texas (Loeblich and Tappan, 1961), and was subsequently observed in late Cenomanian–early Turonian limestones of the Green-

<p>| TABLE 1. K-Ar ANALYTICAL RESULTS OBTAINED FOR THE WHITE MICA CONCENTRATES EXTRACTED FROM THE CHUPADERO SHEAR ZONE |</p>
<table>
<thead>
<tr>
<th>Sample</th>
<th>Lat (N)</th>
<th>Long (W)</th>
<th>% K</th>
<th>40Ar* (mol/g) × 10^-10</th>
<th>% 40Ar*</th>
<th>Age (Ma) ± 1σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCH4</td>
<td>20°56’38.32”</td>
<td>100°27’06.24”</td>
<td>5.67</td>
<td>8.31</td>
<td>95.5</td>
<td>82.6 ± 1.1</td>
</tr>
<tr>
<td>FCH6</td>
<td>20°56’38.32”</td>
<td>100°27’06.24”</td>
<td>6.44</td>
<td>9.12</td>
<td>97.7</td>
<td>79.9 ± 1.0</td>
</tr>
<tr>
<td>FCH17</td>
<td>20°54’59.12”</td>
<td>100°27’36.53”</td>
<td>3.42</td>
<td>4.78</td>
<td>89.5</td>
<td>78.9 ± 1.2</td>
</tr>
</tbody>
</table>
horn Formation exposed in Kansas, Wyoming, and North Dakota (Fig. 7F; Eicher and Worstell, 1970). The concurrent ranges of the foraminiferal association identified in the analyzed samples indicate that the sampled part of the Españita formation is late Cenomanian–early Turonian in age (Fig. 7F). Such an age range coincides with a global sea-level rise that favored the introduction of nutrient-rich oceanic waters and the consequent establishment of anoxic conditions (Schlanger and Jenkyns, 1976; Wilson and Norris, 2001; Keller et al., 2008; Mort et al., 2007; Ifrim et al., 2011; Núñez-Useche et al., 2014). This global anoxic event is well reflected in the foraminiferal association of the Españita formation; the observed foraminifera are opportunistic planktic species that are characteristic of stressed environments. *Muricohedbergella planispira* is characterized by a simple morphology and is considered a cosmopolitan ecological opportunist adapted to eutrophic conditions (Leckie, 1987; Premoli Silva and Sliter, 1994; Keller and Pardo, 2004). Whiteinellids such as *Whiteinella brittonensis* and *Whiteinella aprica* are unspecialized strategists with a high tolerance for eutrophic and anoxic environments (Premoli Silva and Sliter, 1999; Coccioni and Luciani, 2004). Moreover, planktic foraminifera observed in samples from the Españita formation commonly display radially elongated chambers. The chamber elongation has been interpreted as an advantageous morphological character for eutrophic conditions and low oxygen levels (Coxall et al., 2007).

The fact that at least the analyzed part of the Españita formation was deposited during the late Cenomanian–early Turonian oceanic anoxic event may explain the ubiquitous occurrence of radiolarians in the collected limestone samples. In fact, the proliferation of radiolarians is typically interpreted as the first signal of introduction of high concentration of nutrients in oceanic waters and consequent decrease of oxygen levels in the marine environment (Coccioni and Luciani, 2004; Kędzierski et al., 2012).
We collected three samples from the Chupadero shear zone for K-Ar dating of white mica concentrates. We collected two samples (FCH4 and FCH6) from exposures of the Chupadero shear zone located along the southern side of Chupadero Creek, and we collected the third sample (FCH17) 500 m southwest of Charape de Pelones (Fig. 5). We obtained K-Ar ages of 82.6 ± 1.1, 79.9 ± 1.0, and 78.9 ± 1.2 Ma for white mica concentrates extracted from samples FCH4, FCH6, and FCH17, respectively (Table 1). The percentage of radiogenic Ar in the analyzed samples varied from 89.5 to 97.7 (Table 1), indicating small to very small atmospheric contamination. All of the dated samples yielded ages that are younger than the depositional age of the Sierra de los Cuarzos stratigraphic succession; therefore, we interpret the ca. 83–79 Ma age range as the time of crystallization of white mica during the deformation along the Chupadero shear zone. This interpretation is supported by petrographic observations where white mica in samples from the Chupadero shear zone is aligned along the S1 foliation or forms mica fish in microlithons domains, suggesting an origin intimately related to a major deformation event.

**DISCUSSION**

Our new paleontologic and geochronologic data from the Sierra de los Cuarzos allow integration of the previously reported ages for the shortening deformation in central Mexico and permit a test of the hypothesis of a possible relationship between the accretion of the Guerrero terrane and the development of the MFTB.

**Age of Shortening in the Sierra de los Cuarzos and Implications for the Evolution of the Westernmost Part of the MFTB**

Our paleontological determinations indicate that at least part of the pelagic limestones of the Españita formation was deposited in the late Cenomanian–early Turonian time interval. This time interval postdates the shortening deformation that produced major shear zones and folds in the Sierra de los Cuarzos stratigraphic record. A post–late Cenomanian–early Turonian age for the deformation in the Sierra de los Cuarzos is supported by our geochronologic data obtained from the Chupadero shear zone. In fact, K-Ar ages from muscovite concentrates document that the deformation in the Sierra de los Cuarzos took place between 83 and 79 Ma. Such an age range for the deformation in the Sierra de los Cuarzos partly contrasts with the previously proposed timing of shortening in the MFTB along the Zihuatanejo-Guanajuato-Tamazunchale transect. It was previously postulated that the beginning of shortening and uplift in the westernmost part of the MFTB was marked by the rapid drowning of carbonate platforms developed in the Mexican continental interior and the incursion of turbidites of the Soyatal Formation, which are ubiquitously exposed...
between Toliman and San Joaquin (Figs. 4 and 8A; Hernández-Jáuregui, 1997; Fitz-Díaz et al., 2012, 2014). Based on this interpretation, the beginning of the shortening deformation in the westernmost part of the MFTB was bracketed to the late Cenomanian–early Turonian by the fossil association contained in the basal strata of the Soyatal Formation (Fig. 8A; Fitz-Díaz et al., 2014). However, the presence of the Españoita formation in the Sierra de los Cuarzos suggests that during the late Cenomanian–early Turonian time interval the westernmost MFTB was a topographic low accommodating pelagic sediments rather than an orogenic high. This indicates that the westernmost part of the MFTB was not yet shortened and uplifted by the beginning of deposition of the Soyatal Formation. In light of this, the interpretation of the Soyatal Formation as the syntectonic clastic wedge related to the development of the western part of the MFTB needs to be reviewed (e.g., Hernández-Jáuregui, 1997; Fitz-Díaz et al., 2012, 2014). Unfortunately, detailed petrographic data constraining the provenance of turbidites of the Soyatal Formation are not available. Therefore, identifying the source of the Soyatal Formation and determining if this unit really represents a syntectonic clastic wedge related to an orogenic uplift remains a key issue that needs to be addressed. Based on available stratigraphic and structural data from the Zihuatanejo-Guanajuato-Tamazunchale section, three possible hypotheses can be postulated for the tectonic setting under which the Soyatal Formation was deposited. In hypothesis A, turbidites of the Soyatal Formation may have been sourced by the Guerrero terrane (Fig. 8B). This hypothesis relies on the fact that, after its late Aptian accretion, the Guerrero terrane underwent a subsequent event of shortening during late Cenomanian time (Centeno-García et al., 2008; Martini et al., 2009; Martini and Ferrari, 2011). This shortening event produced uplift and subaerial exposure of the marine volcanic arc successions exposed between Zihuatanejo and Huetamo (Fig. 8B), and coincides in age with the onset of deposition of the Soyatal Formation (Centeno-García et al., 2008; Martini et al., 2009; Martini and Ferrari, 2011). Therefore, according to this hypothesis, the beginning of

![Figure 8](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/12/4/1257/3335761/1257.pdf)
deposition of the Soyatal Formation would be associated with a major tectonic event that produced the regional-scale shortening and uplift of the Mexican Pacific margin during late Cenomanian time (Fig. 8B). Alternatively, in hypothesis B, the Soyatal Formation may have been derived from coeval carbonate platforms that were developed on basement highs in the Mexican continental interior before the formation of the MFTB (Fig. 8C). In this case, turbidites of the Soyatal Formation were not sourced by an uplifting orogenic high, as inferred by previous authors, and a syntectonic origin for these deposits should be reassessed. In hypothesis C, the Soyatal Formation may be a composite unit that is made up of deposits derived from the uplifted arc successions of the western part of the Guerrero terrane, as well as deposits sourced by coeval carbonate platforms in the Mexican continental interior (Fig. 8D). A similar scenario with interfingered deposits derived from an orogenic front and from carbonate platforms within the foreland basin was documented by Critelli et al. (2007) for the central Apennines in Italy.

The novel hypotheses presented in this work are speculative at this time and a thorough petrologic study is required in order to understand with more certainty the origin of the Soyatal Formation. In any case, the age of the base of this clastic unit should no longer be considered a chronological constraint for the beginning of shortening deformation in the Mexican continental interior, because our data preclude the possibility of a genetic relationship between the MFTB and the Soyatal Formation.

Figure 9. Schematic synthesis of the Cretaceous–Eocene shortening evolution of central Mexico along the Zihuatanejo-Guanajuato-Tamazunchale transect based on the integration of our new paleontologic and K-Ar geochronologic data with ages reported by previous authors. According to our reconstruction, at least two major orogenic belts are superposed in central Mexico, marking two different stages of the evolution of the North American Pacific margin. (A) One of these belts is represented by the Guerrero terrane suture boundary, which resulted by the accretion of the Guerrero terrane arc assemblages to the Mexican continental interior during the late Aptian. (B) After the accretion, this suture boundary was superposed by an ~650-km-wide, late Cenomanian–Eocene fold-thrust belt, which developed progressively from the western part of the Guerrero terrane into the Mexican continental interior as the contractile front migrated from the Pacific trench to the east.
Cenomanian–Santonian turbidites of the Soyatal Formation are potential candidates to represent the syntectonic clastic wedge derived from the orogenic uplift in the western Guerrero terrane. During the third stage, the contractual deformation shifted to the east (Fig. 9B). Such an eastward migration of the deformation is well documented by Ar-Ar and K-Ar ages between 83 and 75 Ma yielded by illite and muscovite concentrated extracted from major shortening structures in the western MFTB, between the Sierra de los Cuarzos and San Joaquin (Fitz-Díaz and van der Pluijm, 2013; Fitz-Díaz et al., 2014; Garduño-Martínez et al., 2015; this work). Syntectonic foreland deposits associated with this shortening stage are represented by Campanian–Maastrichtian turbidites of the Méndez Formation (Suter, 1987; Fitz-Díaz et al., 2014). The fourth stage of deformation is characterized by a further eastward shift of the contractual front (Fig. 9B), as documented by the 64 Ma Ar-Ar age obtained on illite from a fold train in the eastern part of the MFTB, south of El Lobo (Fitz-Díaz et al., 2014). During this deformational stage, foreland deposits are represented by the Paleocene Velasco and Chicontepec Formations, which are exposed in the easternmost part of the MFTB (Suter, 1987; Fitz-Díaz et al., 2014). The Velasco and part of the Chicontepec Formations were incorporated into the orogenic wedge during the Eocene, marking the fifth stage of the shortening evolution (Fig. 9B; Fitz-Díaz et al., 2014). A similar structural evolution characterized by the trenchward shift of the shortening deformation after the Guerrero terrane accretion and the subsequent eastward migration of the contractual front between Cenomanian and Paleocene time has been also documented along another east-west transect that extends 150–200 km to the north of the Sierra de los Cuarzos (Cuellar-Cardenas et al., 2012).

The geochronologic framework of the shortening deformation obtained by integrating our new data with previous isotopic and paleontologic ages permits a test of the possible relationship between the accretion of Guerrero terrane and the development of the MFTB along the Zihuatanejo–Guanajuato–Tamazunchale transect. Some proposed that the collision and accretion of the Guerrero terrane represented the main cause for the development of the MFTB in the Mexican continental interior (Fig. 2A; Coney et al., 1980; Campa and Coney, 1983; Mendoza and Suástegui, 2000; Keppie, 2004; Talavera-Mendoza et al., 2007). According to this hypothesis, one should reasonably expect that the shortening deformation was transferred from the Guerrero terrane suture boundary into the Mexican continental interior after the accretion (Fig. 2A); however, available data indicate that after the late Aptian Guerrero terrane accretion the shortening deformation shifted trenchward rather than inboard, and subsequently migrated from the western part of the Guerrero terrane into the Mexican continental interior between late Cenomanian and Eocene time (Figs. 9A, 9B). In light of this reconstruction, the shortening structures in the western part of the MFTB do not show any in-sequence relationship with the adjacent Guerrero terrane suture belt. On the contrary, our K-Ar data indicate that shortening in the westernmost part of the MFTB took place in early Campanian time, ~30 m.y. later than the late Aptian accretion of the Guerrero terrane. Based on these considerations, we suggest that a geodynamic scenario in which collision of the Guerrero terrane is the cause for shortening deformation in the Mexican continental interior needs to be reassessed (Fig. 2A). Alternatively, we favor the interpretation that at least two major orogenic belts are superposed in central Mexico, marking two different stages of the evolution of the North American Pacific margin (Fig. 2B). One of these belts is represented by the Guerrero terrane suture boundary exposed at Guanajuato. This suture boundary is an ~80-km-wide fold-thrust belt produced by the accretion of the Guerrero terrane to the Mexican continental interior in late Aptian time, ca. 115 Ma. After accretion, this suture boundary was superposed by an ~650-km-wide, late Cenomanian–Eocene fold-thrust belt, which developed progressively from the western part of the Guerrero terrane into the Mexican continental interior as the contractual front migrated from the Pacific trench to the east. The cause for such a wide orogenic belt remains the subject of debate (Cuellar-Cardenas et al., 2012; Fitz-Díaz et al., 2012; Martini et al., 2012).

At present, evidence for collision of other juvenile arc terranes after late Aptian accretion of the Guerrero terrane have not been recognized along the Pacific margin of central and southern Mexico. Excluding terrane accretion as a possible cause for the late Cenomanian–Eocene shortening, variation in convergence rates and changes in subduction directions along the Mexican Pacific trench accompanied by gravitational collapse of the uplifting continental crust (e.g., Solari et al., 2007; Cuellar-Cardenas et al., 2012) appear to be the most viable mechanisms that shaped the Pacific margin of southern North America during Late Cretaceous and early Paleogene time.

CONCLUSIONS

Our new geochronologic data constrain the shortening deformation in the Sierra de los Cuarzos between 83 and 79 Ma. Such an age range implies the following.

1. The late Cenomanian–Santonian turbidites of the Soyatal Formation do not represent a syntectonic clastic wedge associated with the first stage of development of the MFTB, and therefore the age of the base of this unit should no longer be considered a constraint for the timing of shortening deformation in the Mexican continental interior.

2. The onset of shortening and uplift in the MFTB along the Zihuatanejo–Guanajuato–Tamazunchale transect is ~10 m.y. younger than previously assumed.

3. The shortening structures in the western part of the MFTB were developed ~30 m.y. later than the accretion of the Guerrero terrane and do not show any in-sequence relationship with the adjacent Guerrero terrane suture belt. This suggests that the late Aptian Guerrero terrane suture boundary and the late Cenomanian–Eocene MFTB may represent two distinct orogens that mark two different stages of the evolution of the North American Cordillera.

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