Long lasting interactions between tectonic loading, unroofing, post-rift thermal subsidence and sedimentary transfers along the western margin of the Gulf of Mexico: Some insights...

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Long lasting interactions between tectonic loading, unroofing, post-rift thermal subsidence and sedimentary transfers along the western margin of the Gulf of Mexico: Some insights from integrated quantitative studies

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ABSTRACT

After Jurassic rifting, numerous carbonate platforms (i.e., the Orizaba, Cordoba and Golden Lane–Tuxpan platforms) developed during the Lower and Middle Cretaceous episode of thermal subsidence along the western passive margin of the Gulf of Mexico, with intervening basinal domains (i.e., the Tampico-Misantla, Zongolica, Veracruz and Deep Gulf of Mexico – DGM – basins).

During the Late Cretaceous–Paleocene, the east-verging Sierra Madre Oriental thrust belt developed, resulting in tectonic uplift and unroofing of the allochthonous units (i.e. tectonic units made up of former Orizaba and Cordoba platforms and Zongolica Basin series). This new topography provided also an important source of clastics to feed the adjacent foredeep, where coeval tectonic loading accounted for the bending of the foreland lithosphere. However, shallow water facies or even emersion persisted until the Eocene in the forebulge area (at the present location of the Golden Lane), preventing locally the clastics to reach the DGM. This topographic barrier was ultimately bypassed by the clastics only during the Oligocene and Neogene, once (1) the prograding clastic wedge had exceeded accommodation, and (2) the long lasting thermal subsidence of the passive margin could overpass the effect of the bending and force the former bulge to sink.

Numerous paleo-thermo-meters (Tmax, Ro), paleo-thermo-barometers (fluid inclusions), PVT and coupled forward kinematic and thermal modeling have been used to calibrate and date the progressive unroofing of the thrust belt. Coupled tectonic and sedimentologic modeling was applied in the foreland to predict the distribution of sand versus shale ratios in the Oligocene to Plio-Quaternary clastic sedimentary wedge of the passive margin, where gravitational gliding of post-Eocene series occurred during the Neogene along major listric faults.

Mantle dynamics are advocated as the main process accounting for post-orogenic uplift and regional tilting of the basement, which initiated a massive transfer of sediments from the Cordillera towards the Gulf of Mexico, from Oligocene onward, resulting in a destabilization and gravitational collapse of the western slope of the Gulf of Mexico in Neogene times.

1. Introduction

Unlike Atlantic passive margins, which mostly developed away from the main Alpine thrust fronts, the evolution of the western margin of the Gulf of Mexico has been strongly impacted by the conjugate effects of the Cordilleran orogen and long-lasting subduction of the Pacific Ocean along the western margin of the North American craton (see Bartolini et al., 2003 and references therein).

For instance, the overall post-rift thermal subsidence of the Gulf of Mexico has been locally modified during the Late Cretaceous and Paleogene by the tectonic load applied on the North American lithosphere by the Cordilleran edifice, resulting in the development of a foreland flexural basin at the current location of the coastal plain of the Veracruz State (Wincker and Buffler, 1988; Feng et al., 1994;

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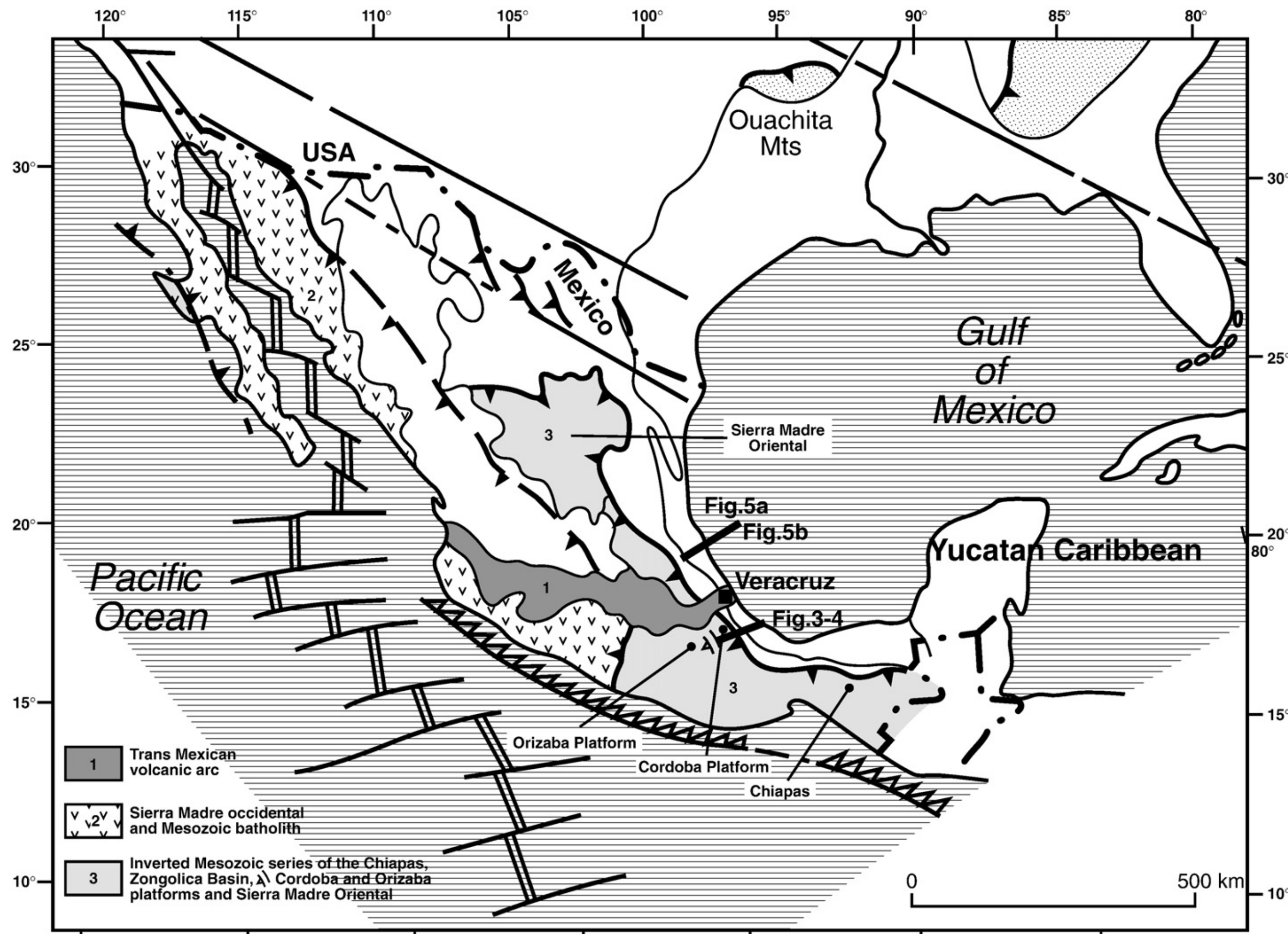


Fig. 1. Simplified structural map of south-eastern Mexico and location of the studied transects.

Feng and Buffler, 1996). Post-orogenic uplift and unroofing of the Cordilleran domain from Oligocene onward have also resulted in a massive sediment transfer from the continent towards the Gulf of Mexico, accounting for a destabilization of the slope and its gravitational collapse (Bryant et al., 1968; Aranda-Garcia, 1999; Wawrzyniec et al., 2003; Roure, 2008).

Integrated field work coupled with petrographic studies, seismic interpretation and basin modeling have been performed in distinct segments of south-eastern Mexico, i.e. in the Cordoba Platform and Veracruz Basin south of the Trans-Mexican volcanic province, as well as farther north in the Sierra Madre Oriental, Golden Lane area and adjacent offshore (Fig. 1). The main results of these studies are presented below, focusing on the subsidence and uplift–unroofing history of the western margin of the Gulf of Mexico, on the description and quantification of resulting sedimentary transfers and reservoir development, as well as on its incidence on the overall fluid flow, hydrocarbon migration and pore-fluid pressure evolution.

2. Geological and geodynamical background

The western margin of the Gulf of Mexico records the long-lasting interactions between extension and thermal subsidence of a passive margin on the one hand, and Cordilleran compression and related foreland flexure development on the other hand. The main steps of this complex geodynamic evolution can be summarized in the following sections.

2.1. Jurassic rifting and opening of the Gulf of Mexico

The pre-rift substratum of the western Mexican margin is a composite of igneous and metamorphic rocks, with local occurrence of Paleozoic sedimentary strata.

Synrift Jurassic series are locally exposed in south-eastern Mexico, i.e. in the vicinity of the Chiapas Massif, and are made up of continental red beds (Todos Santos Formation). Numerous Jurassic normal faults are also imaged on seismic profiles, and have controlled the location of the main Jurassic depocenters, and the lateral extent of source rocks and salt horizons.

Magnetic anomalies in the deep part of the Gulf of Mexico testify for its oceanic character, the age of drifting being restricted to the Late Jurassic (Moore and del Castillo, 1974; Anderson and Schmidt, 1983; Ewing, 1991).

2.2. Cretaceous thermal subsidence and progradation of carbonate platforms

During the Lower Cretaceous, thick carbonate platforms developed on top of former Jurassic horsts, prograding laterally towards the intervening deeper water basins. Two Cretaceous platform domains have been widely documented in the study area: the Golden Lane–Tuxpan Platform in the north, which still belongs to the foreland autochthon of the Cordillera and extends in the subsurface in the vicinity of the Coastal Plain (Viniegra and Castillo-Tejero, 1970; Coogan et al., 1972; Galicia, 2001), and the Cordoba Platform in the south, which has been tectonically accreted to the Cordilleran allochthon during the Late Cretaceous to Eocene Laramide orogeny, and is currently cropping out in the foothills (Figs. 1 and 2; Ortuño, 1991; Rojas, 1999; Meneses-Rocha et al., 1997).

Cretaceous basinal facies occur both east and west of the Cordoba Platform, i.e. in the subsurface of the Veracruz Basin within the autochthonous foreland in the east, and in the outcrops of the Zongolica thrust units in the west, within the Cordilleran allochthon, respectively (Figs. 1–4).

Farther north, Mesozoic basinal facies are documented by exploration wells only west of the Golden Lane–Tuxpan Platform, but they can also be traced on seismic profiles east of this isolated reefal domain over the entire offshore domain (Figs. 1, 5 and 6).

2.3. Late Cretaceous to Eocene Cordilleran deformation and development of the foreland flexure

East-verging thrust units of the Sierra Madre Oriental and Zongolica fold-and-thrust belts were progressively emplaced during the Late Cretaceous until the Eocene, synchronously with the Overthrust Belt in the US and the Canadian Rockies farther north, resulting in the sinking of former platform domains, and the development of a foreland flexural basin at the present location of the Coastal Plain. Siliciclastic turbidites of the Chicontepec Formation and then shallower water sandstones and clays progressively filled in this trough (Fig. 2).

2.4. Neogene transpression, clastic sedimentation and gravitational collapse of the margin

From Oligocene onwards, erosional products of the Cordillera were transferred to the Gulf of Mexico, the former Laramide foredeep basin being also progressively uplifted and exhumed by erosion.

Huge volumes of siliciclastic series were progressively deposited across the margin, resulting in a generalized gravitational collapse of both the western and north-western margins of the Gulf of Mexico. However, the structural styles of these two systems are quite distinct, being mostly driven by the mobility of the Jurassic salt in Texas (Fiduk et al., 1999; Rowan et al., 1999a,b; Trudgill et al., 1999), whereas undercompacted and overpressured Eocene clays are assumed to control the localization of the deformation off the Veracruz shore in south-eastern Mexico.

Apart of this up-slope gravity-driven extension and coeval compression at the toe of the slope, which is limited to the Cenozoic sedimentary cover, the overall Oligocene and Neogene tectonic regime operating in deeper horizons and within the basement of the former Cordilleran foreland still remains debated (Reed, 1994, 1995):

- 1) True compression is well documented in the southern part of the Gulf of Mexico, with the Neogene basin inversion and tectonic contraction in the Chiapas foothills as well as along the western margin of the Yucatan block, where it accounts for the structural closures of the Cantarel field (Mitra et al., 2005).
- 2) Oligocene crustal extension has been also evidenced recently below the gravitational structures along deep seismic profiles recorded across the north-western Texas margin of the Gulf of Mexico (Rangin et al., 2008a,b).
- 3) In between, Neogene transpressional inversion features are documented locally in the Veracruz Basin (Fig. 4), but also in the offshore of the Veracruz State, near the transition between oceanic and continental crust, beneath the main intra-Eocene décollement level (Mossman and Viniegra, 1976; Le Roy, 2007; Andreani, 2008; Andreani et al., 2008a,b; Le Roy et al., 2008).

3. Seismic imagery and construction of the present-day structural sections

Petroleum exploration has been very active both south of the Trans-Mexican volcanic province in the Veracruz Basin and farther north, in the vicinity of the Golden Lane, resulting in a good control on the overall architecture of the basement between the Cordilleran thrust front in the west, and the Gulf of Mexico in the east. Seemingly, good quality seismic profiles have been recorded by Pemex in the offshore, thus providing a continuous control on the present architecture of the basement from the Cordilleran foreland to the deep abyssal plain.

In contrast, only few, poor quality seismic profiles have been recorded across the thrust belt itself, west on the productive structures of the Laramide thrust front. Although these profiles can hardly control the distribution of Jurassic synrift sequences within the

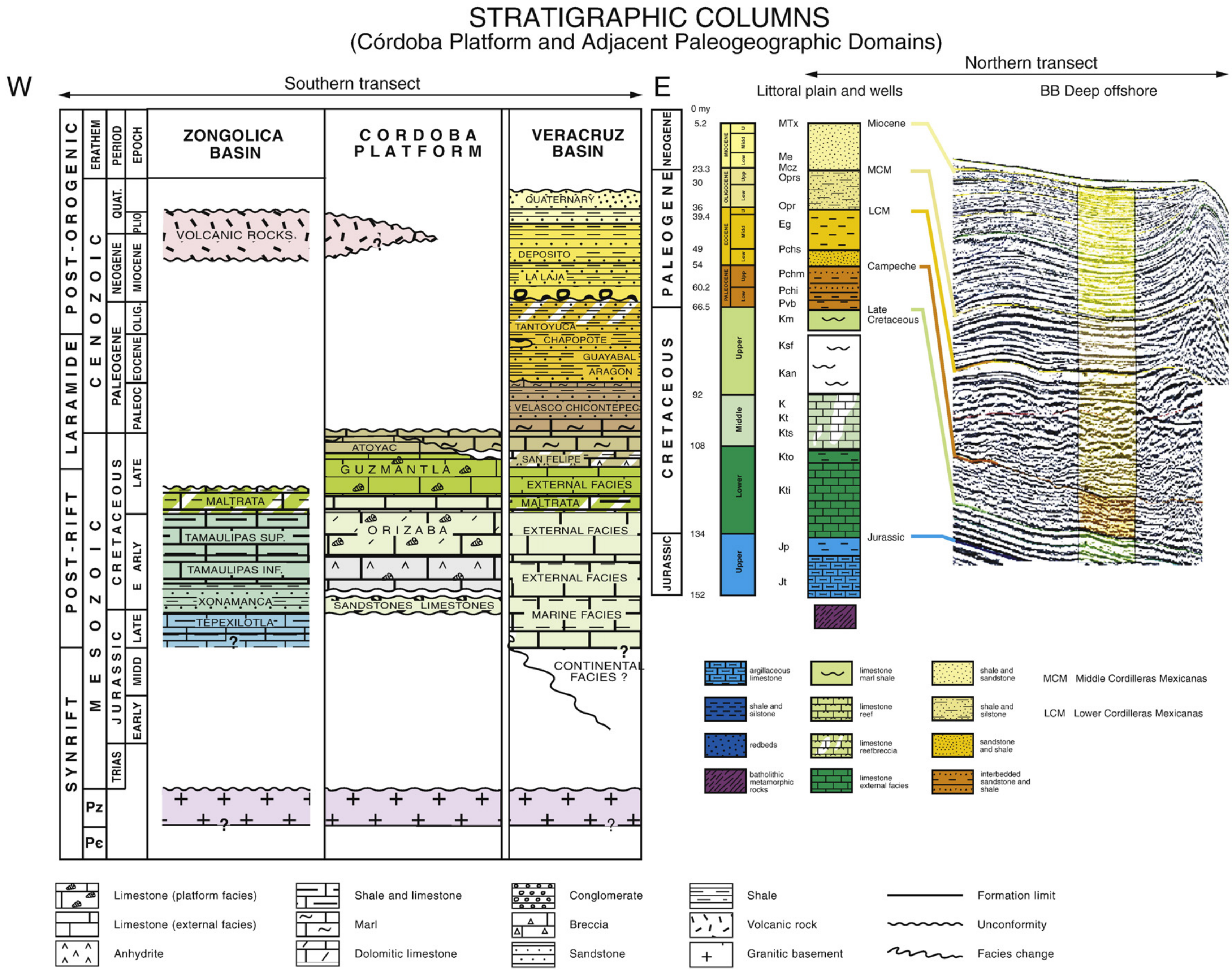


Fig. 2. Synthetic lithostratigraphic columns representative of the main tectonic units.

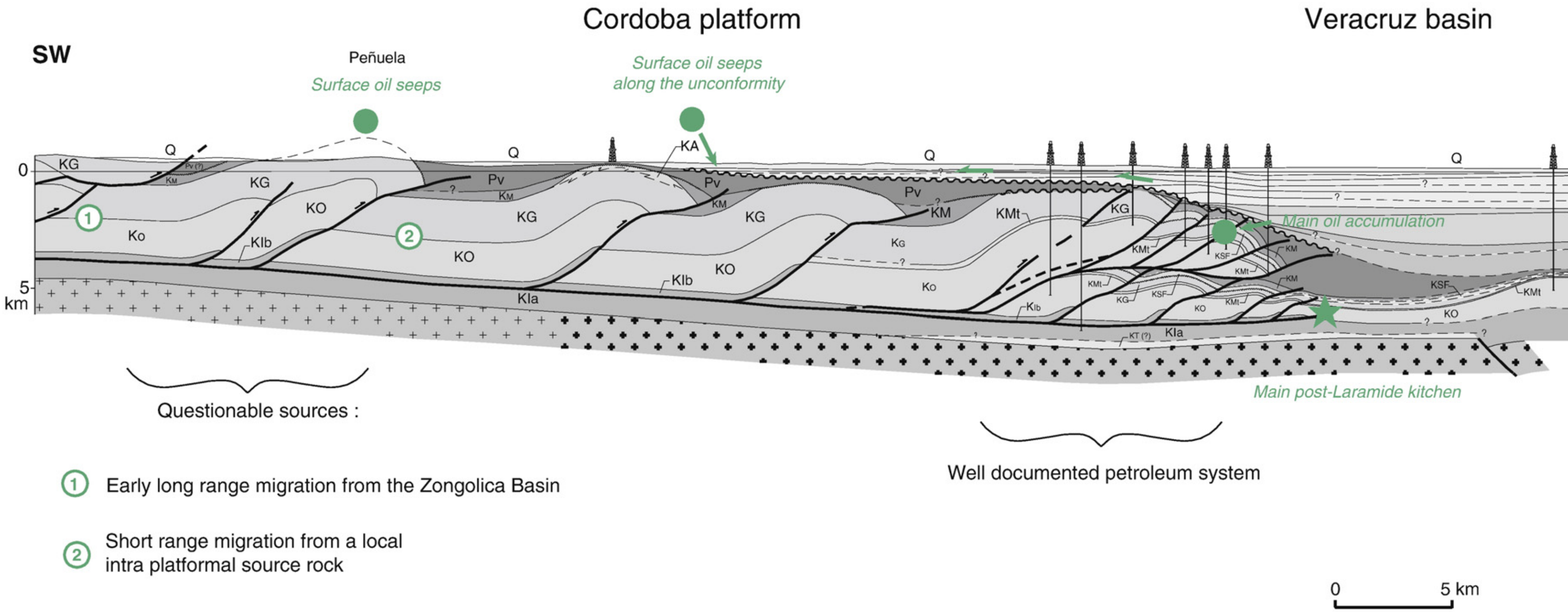


Fig. 3. Present-day architecture of the Cordoba Platform and Cordilleran thrust front outlining the east-dipping attitude of the basement and hydrocarbon habitats (after Ortuño et al., 2003; modified). K1a and K1b: Neocomian–Aptian; KO: Orizaba Formation, Albian–Cenomanian; KG: Guzmantla Formation, Turonian–Campanian; KM: Mendez Formation, Maastrichtian; Pv: Paleocene Velasco Formation. See location in Fig. 1.

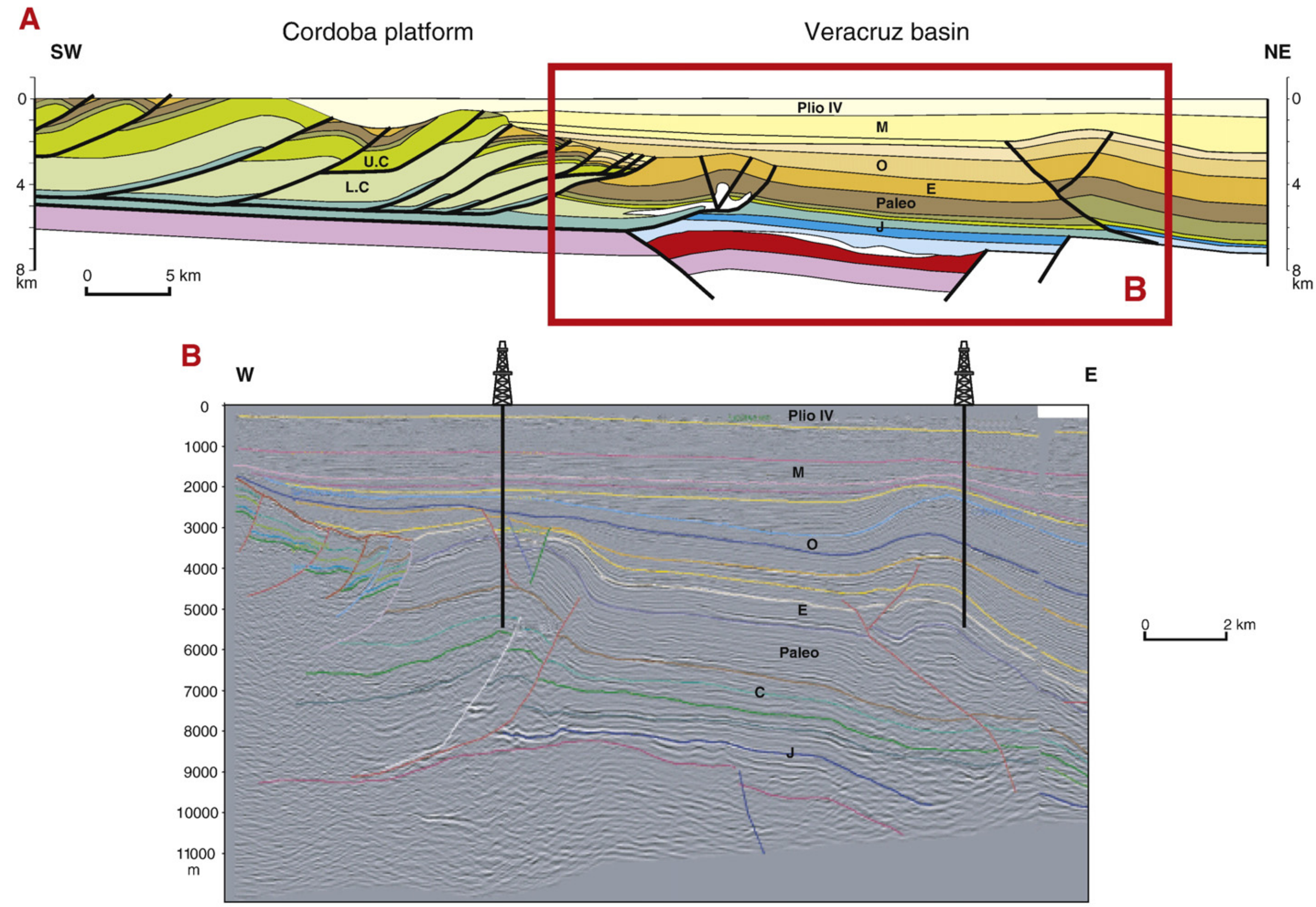


Fig. 4. A) Structural cross-section of the western part of the Veracruz Basin and Laramide thrust front. B) Seismic profile outlining Neogene transpressional foreland inversions in the western part of the Veracruz Basin (after Gonzalez-Mercado, 2007; Gonzalez-Mercado et al., 2008; modified). See location in Fig. 1.

foothills domain, they help in tracing the presently east-dipping attitude of the intra-Cretaceous basal décollement. Shallower thin-skinned thrust units and surface anticlines are dominantly made up of Lower Cretaceous platform carbonates, the erosional remnants of former Late Cretaceous to Eocene siliciclastic series being now restricted to the poorly exposed synclines (Fig. 2).

Two regional cross-sections have been studied and modeled during this study, the first one in the south, across the Cordoba Platform and Veracruz Basin (Figs. 3 and 4), the other one farther north across the Chicontepec Basin, the Golden Lane and adjacent offshore (Figs. 5 and 6). Their present depth architecture, which is adequately controlled by seismic data, is briefly described below (for more details, especially for the velocity models applied for the time to depth conversion, see Ortuño et al., 1999, 2003; Ferket, 2006; Gonzalez-Mercado, 2007; Alzaga-Ruiz et al., 2009a,b).

3.1. The Cordoba–Veracruz transect (southern section)

This southern section images two contrasted structural domains, i.e. the Veracruz Basin in the east, and the Cordoba Platform and Zongolica thrust belt in the west (Fig. 3). Sedimentation was more or less continuous from the Jurassic to Present in the Veracruz Basin, accounting for more than 5 km of Oligocene to Neogene post-orogenic sequences (Jennette et al., 2003a,b), whereas the Cordoba Platform was instead deeply eroded during and after the Cordilleran orogeny.

In the western part of the section, the Zongolica thrust belt is made up of various thrust units derived from three distinct Mesozoic paleogeographic domains, i.e. the Orizaba Platform in the west and the Cordoba Platform in the east, with the intervening Zongolica Basin (Ortuño et al., 1999, 2003).

The eastern front of the thrust belt is made up of an anticlinal stack of duplexes, localized at the transition between the former Cordoba Platform domain and the adjacent Mesozoic basinal series of the Veracruz Basin. These duplexes contain the most productive reservoirs, which are made up of Cretaceous platform limestone, slope breccias or coarse dolomite.

Cordilleran thin-skin frontal structures are sealed by Paleocene seals and Oligocene to Pliocene molasses, with no sign of Neogene reactivation. In contrast, high-angle basement-involving faults and Jurassic grabens of the Veracruz Basin were locally reactivated and inverted during the Neogene, as evidenced by antithetic reverse faults deforming the Neogene series (Fig. 3). Although we could not find evidence for associated strike-slip faulting on east-trending 2D seismic profiles, we assume a lot of transpression was associated with this basement inversion, as evidenced by Andreani (2008) and Andreani et al. (2008a,b), based on more systematic seismic interpretation and microtectonic studies.

In both time and depth-converted sections, the infra-Cretaceous substratum displays a regular east-dipping attitude beneath the foothills, and remains about parallel to the Pliocene unconformity in the vicinity of the Laramide thrust front, most if not all this tilt being interpreted as post-Laramide in age.

Because the quality of the seismic remains poor beneath the foothills, the few low amplitude deformations observed at the level of the basal décollement level could be interpreted either as (1) velocity artefacts (pull-ups beneath the surface anticlines and pull-

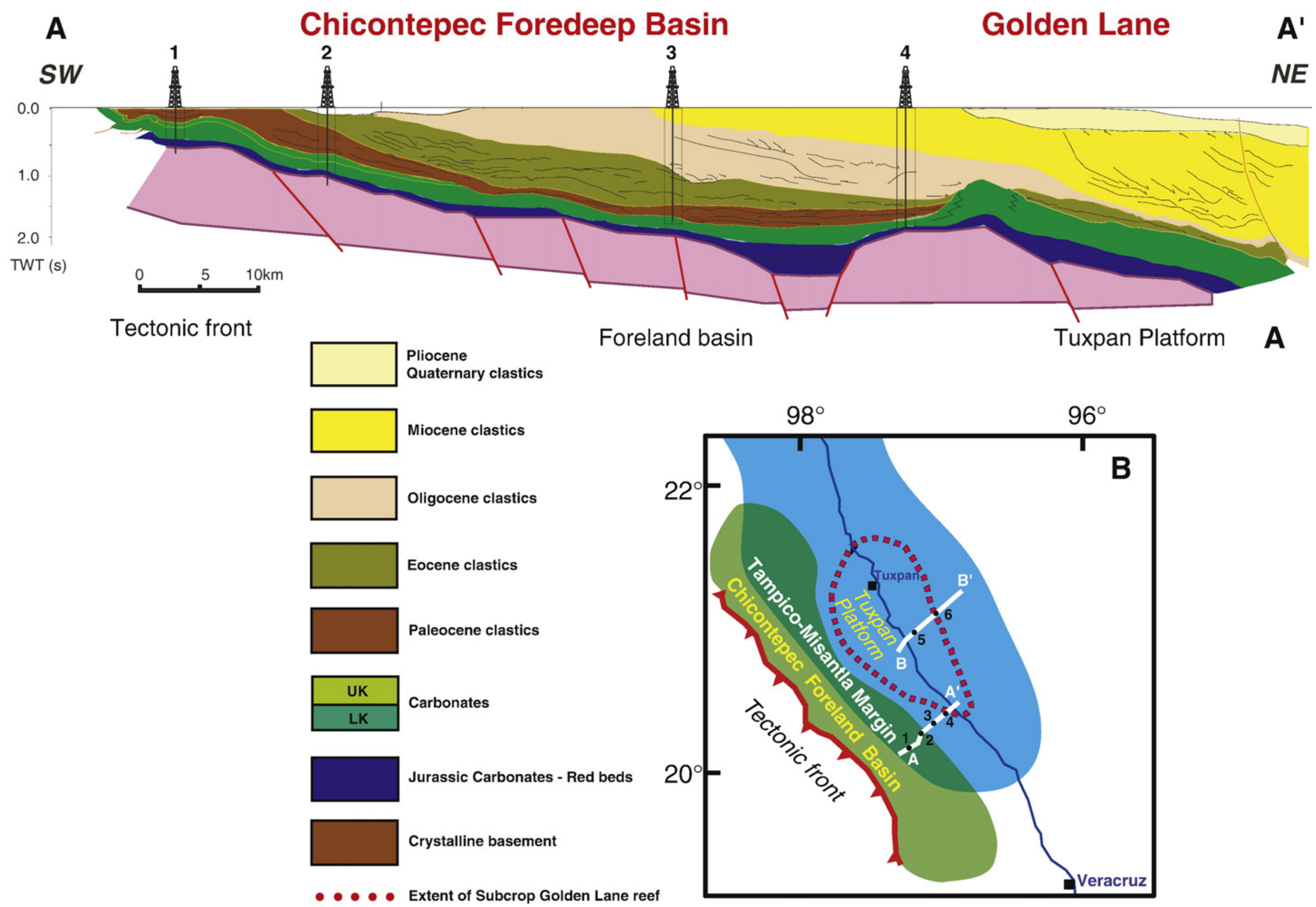


Fig. 5. Structural section across the Chicontepec tilted foredeep basin and Golden Lane–Tuxpan Platform (after Alzaga-Ruiz, 2008; Alzaga-Ruiz et al., 2009a,b; modified). See location in Fig. 1.

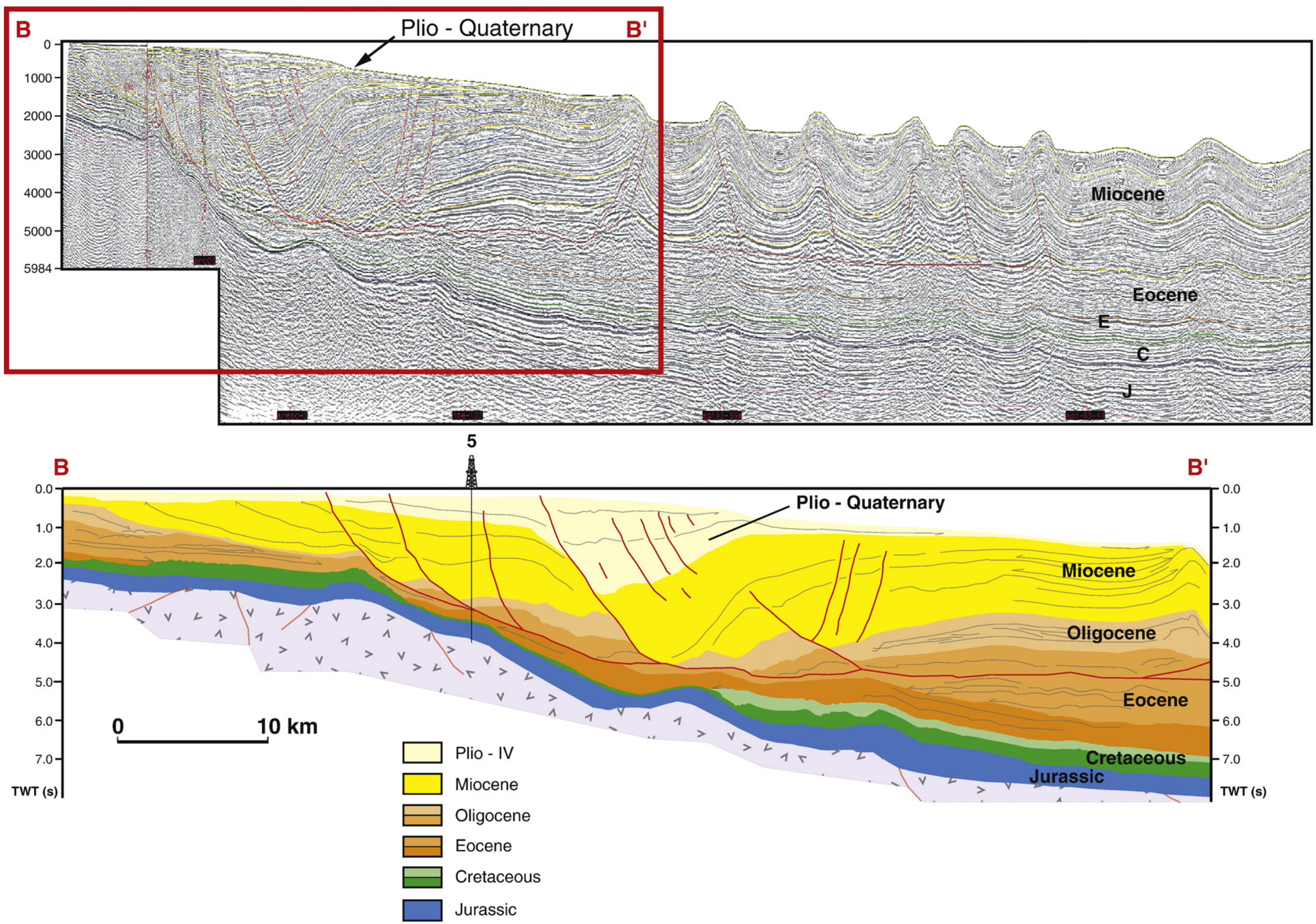


Fig. 6. Eastward extent of the same regional section across the offshore, outlining the gravitational collapse of the Neogene series, with development of a large listric fault and associated half-graben and roll-over feature in the vicinity of the shelf break, and compressional features at the toe of the slope (after Alzaga-Ruiz, 2008; Alzaga-Ruiz et al., 2009a,b; modified). See location in Fig. 5.

downs beneath the synclines), or as (2) post-Laramide inversion of underlying Jurassic grabens (Fig. 3). Further gravimetric studies or seismic reprocessing would be indeed required to test these different hypotheses.

3.2. The Chicontepec–Golden Lane–Offshore transect (northern section)

The northern section can be subdivided into three distinct structural domains, i.e. the Chicontepec Basin in the west, the Golden Lane–Tuxpan Platform, located in the subsurface of the Coastal Plain, and the Offshore, which is characterized by a gravitational collapse of Oligocene and younger siliciclastic series (Buffler et al., 1979; Buffler, 1983; Aranda-Garcia, 1999; Ambrose et al., 2003, 2005; Figs. 5 and 6).

The Chicontepec Basin extends from the Cordilleran thrust front in the west to the Golden Lane in the east. Well imaged on seismic profiles, the substratum of the Chicontepec Basin is made up of an east-dipping pre-rift basement, dissected by numerous Jurassic normal faults. Overlying Jurassic synrift series and Lower Cretaceous basinal series have been evidenced in numerous exploration wells. Subsequent synorogenic series are made up of Late Cretaceous to Eocene turbidites, which are progressively onlapping the western edge of the Golden Lane reefs. They represent synflexural series which were deposited in the former foredeep basin, and are now overlain by post-orogenic Oligocene and Miocene series, which constitute an eastward prograding sedimentary wedge. These post-orogenic series progressively overlapped and by-passed the paleo-relief of the Golden Lane.

Due to post-orogenic uplift of the hinterland, the western part of the flexural basin as well as the Oligocene post-orogenic sedimentary wedge have been strongly tilted and eroded in the western part of the transect, where they are now widely exposed at the surface.

Unlike in the Veracruz Basin, there is no evidence for onshore Neogene compression nor transpression in the seismic profiles imaging the Chicontepec Basin.

Late Cretaceous and Paleogene series are also missing in the Golden Lane area, because this domain was emerged during most of the Cordilleran orogeny. The Golden Lane–Tuxpan Platform is actually located at the former location of the fore-bulge, and started to subside again only during the Neogene.

From Late Cretaceous to Eocene times, erosional products of the Cordillera were either trapped locally in the Chicontepec Basin, or transferred to the deep offshore by transverse canyons located both north and south of the emerged Tuxpan Platfrom (Fig. 1; Galloway et al., 2000).

The most obvious tectonic features in the offshore profiles relate to the gravitational collapse of the Cenozoic sedimentary cover above a basal décollement, which is located within undercompacted–overpressured Eocene shaley intervals. Dominantly east-dipping listric normal faults have developed during the Neogene in the vicinity of the shelf break, i.e. at the place where the prograding sedimentary wedge reached and maintained its maximum thickness. Continuous up-slope extension still accounts for the development of a thick Pliocene half-graben, adjacent to a wide roll-over structure which is almost bald of any Pliocene deposits (Fig. 6). Alternatively, up-slope extension is compensated down-slope by the coeval development of compressional structures at the toe of the slope.

It is worth to mention that Neogene transpressional reactivation of the crystalline basement and inversion of Jurassic faults of the former passive margin were also recently evidenced beneath the basal intra-Eocene décollement on recent deep seismic profiles, near the continent–ocean transition (Le Roy, 2007; Le Roy et al., 2008).

4. 2D forward kinematic and petroleum modeling in the FFTB (Thrustpack/Ceres/Paleo-thermo-barometers)

After depth-conversion and balancing of the regional structural sections, 2D coupled kinematic, fluid flow and petroleum modeling has been performed along the southern section. The most challenging task here was first to reconstruct the eroded thicknesses of the foothills part of the transect, as well as the past attitude of the foreland basement.

4.1. Paleo-thermo-barometers and estimation of the paleo-burial and eroded thicknesses

The inversion of maturity data of the organic matter, i.e. Tmax and Ro, provides realistic constraints for thermal calibration of basin models in foreland areas where sedimentary records are continuous and allow direct controls on the paleo-burial evolution. In foothills areas however, where large erosional episodes occurred, two unknown parameters must be quantified simultaneously: the paleo-burial and the heat flow (or paleo-geothermal gradient); any mistake on one of them resulting in large errors for the second one (Roure et al., 1999, 2005).

Maturity ranks of the organic matter and bottom hole temperatures were extensively used to calibrate, by means of 1D thermal modeling of the most representative wells, the thermal history of the Veracruz Basin, where only limited and localized erosion occurred (Fig. 7; Ferket, 2006; Gonzalez-Mercado, 2007).

In the adjacent foothills, we could use contemporaneous hydrocarbon-bearing and aqueous fluid inclusions from well documented diagenetic cements to derive both the temperature and burial at the time of cementation, assuming a hydrostatic pressure regime and purely conductive thermal transfers (Fig. 8; Ferket, 2006). Assuming from petrography that the two types of inclusions formed in the same PT conditions, we are dealing with two distinct compositional isopleth and isochoric fluid systems. The technique consists in first identifying the precise composition of the fluid inclusions, i.e. the salinity and gas content of aqueous inclusions by micro-thermometry and the nature, composition and density of hydrocarbon-bearing inclusions by FTIR, and then to apply PVT modeling to derive the isochore curves (PT

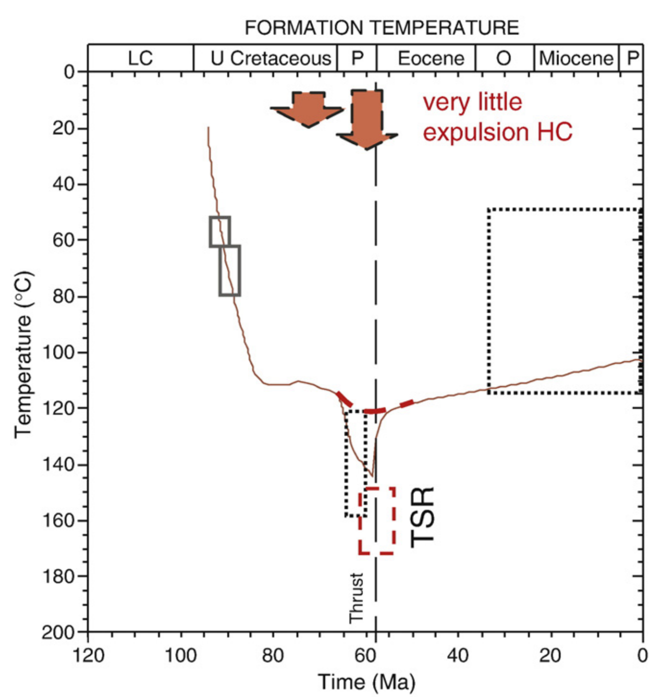
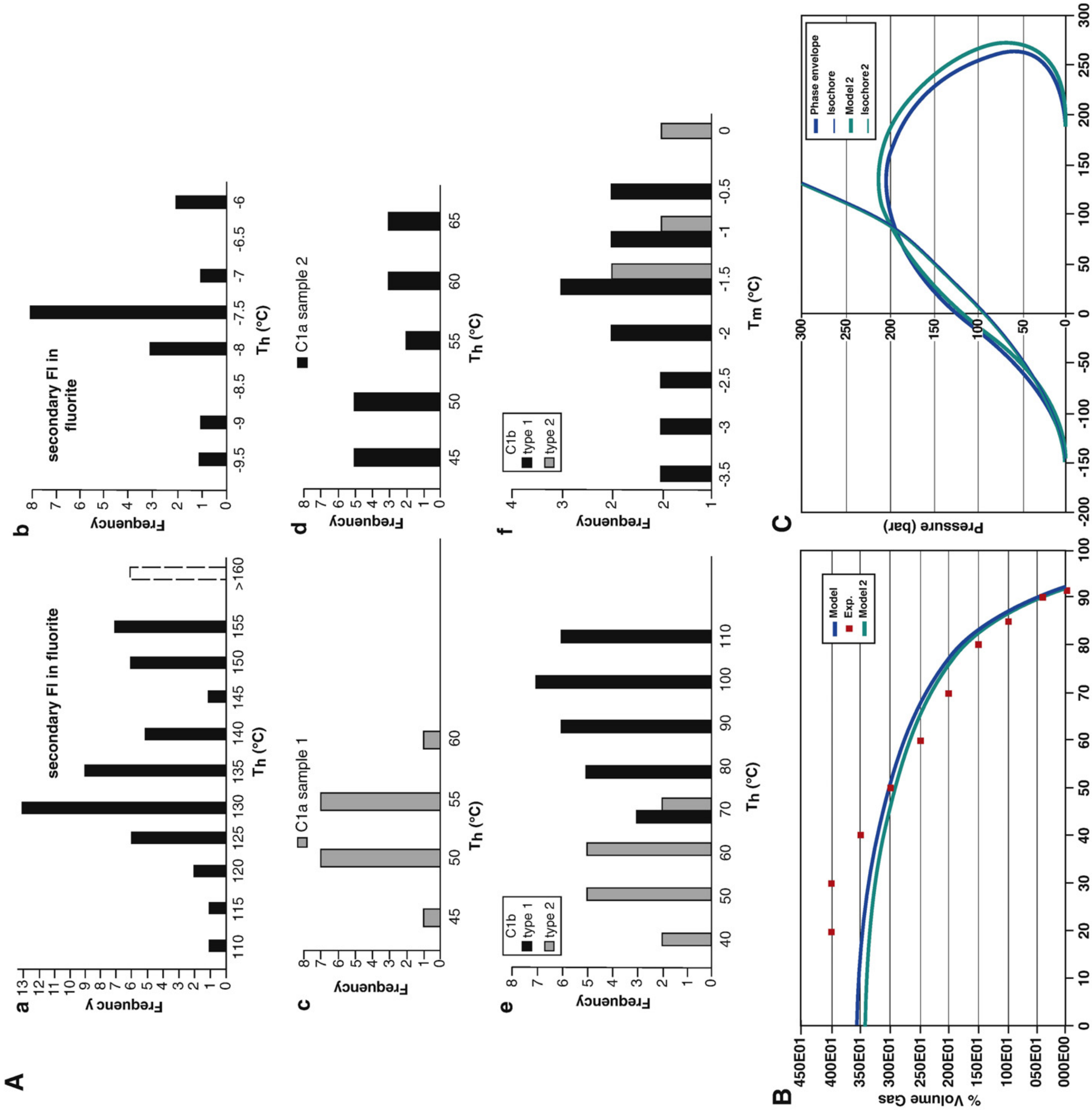


Fig. 7. 1D-Genex modeling aiming at calibrating the heat flow and computing the eroded thicknesses along the southern transect: This diagram shows the final fit between FI data and calculated temperature with an input of 30 mW/m^2 heat flow and high sedimentary/tectonic load, corrected according to PVT results (after Ferket, 2006; Ferket et al., in press, in press-a, in press-b; modified). TSR: Thermo-Sulfate Reduction.


A
a
secondary FI in fluorite
Frequency
Th (°C)
b
secondary FI in fluorite
Frequency
Th (°C)
c
C1a sample 1
Frequency
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d
C1a sample 2
Frequency
Th (°C)
e
C1b
type 1
type 2
Frequency
Th (°C)
f
C1b
type 1
type 2
Frequency
Tm (°C)
B
% Volume Gas
Model
Exp.
Model 2
Temperature (°C)
C
Pressure (bar)
Phase envelope
Isochore
Model 2
Isochore 2
Temperature (°C)

evolution when keeping the volume unchanged) for hydrocarbon system, the intersection of the hydrocarbon isochore at the aqueous fluid homogenization temperature for a specific composition and density providing an accurate estimate of both pressure and temperature at the time of trapping (Guilhaumou and Dumas, 2005; Ferket et al., in press, in press-a, in press-b).

4.2. Forward kinematic modeling and basement architecture

4.2.1. Cordoba–Veracruz transect (southern section)

Former 2D kinematic models performed with Thrustpack across the Cordoba Platform considered only minor erosion in the foothills, assuming an initially flat, horizontal basement in the pre-orogenic stage and during the thrust emplacement, followed by a progressive eastward tilting of the basement from Eocene to Present (Ortuño et al., 1999, 2003).

Eroded thicknesses derived from fluid inclusion studies however indicate that up to 4.5 km of overburden, comprising mainly synflexural Late Cretaceous to Eocene deposits, were removed by erosion from the main anticlines since the onset of thrusting.

New 2D kinematic reconstructions were therefore implemented with Ceres (Ferket, 2006; Gonzalez-Mercado, 2007). According to these new fluid inclusions data, the basement, initially grossly horizontal during the passive margin stages, became down-flexed toward the west during the Campanian, thus allowing sufficient space to accommodate up to 3 to 4 km of synflexural siliciclastic sediments before the onset of thrusting, prior to be uplifted again in post-Eocene times (Fig. 9).

4.2.2. Sierra Madre Oriental–Golden Lane transect (northern section)

Published apatite fission tracks data document the post-Laramide uplift and unroofing of the Sierra Madre Oriental during the Neogene (Gray et al., 2001).

We could also estimate the initial thickness of Late Cretaceous to Eocene flexural sequences in the western portion of the Chicontepec Basin, by extrapolating linearly to the west and above the present erosional surface, the attitude of the main reflectors currently observed in the eastern, not yet eroded part of the basin. However, paleothermometer studies or thermal modelling would still be required to get a better estimate of the eroded thicknesses there.

The initial configuration and paleo-topography of the basement was subsequently restored to its former attitude during the deposition of the flexural sequences, assuming 1 to 2 km of water depth in the deepest part of the basin in the west, coeval with emersion of former Cretaceous reefs in the vicinity of the Golden Lane (Fig. 10; Alzaga-Ruiz, 2008; Alzaga-Ruiz et al., 2009a,b). As evidenced in this retrodeformed section representative of the Cordilleran orogeny, the Golden Lane is best interpreted as a fore-bulge culmination separating the Laramide foredeep in the west from the deep Gulf of Mexico basin in the east, thus preventing a direct transfer of erosional products from the Cordillera to the deep offshore.

Long-lasting thermal subsidence of the margin ultimately overpassed the effects of the vanishing load applied by the Cordilleran allochthon on the foreland lithosphere during Oligocene and Miocene times, resulting in a progressive sinking of the previously emerged Golden Lane–Tuxpan domain (Fig. 10).

4.3. Timing of the unroofing and sediment transfers

Both sections display a current east-dipping attitude of the basement beneath the foothills and adjacent Laramide foredeep basin, which post-dates the end of the tectonic contraction.

Extensive apatite fission tracks data would be required to date precisely the timing of the resulting unroofing, either in the source area (i.e. in the foothills and adjacent parts of the Chicontepec Basin, where the former flexural sequence is widely exposed), but also in redeposited Oligocene, Miocene and Pliocene series, in the sink areas extending from the Veracruz Basin in the onshore, up to the distal portions of the offshore.

Erosion in the foothills operated already during the Late Cretaceous and Paleocene–Eocene times, thus accounting for the thick turbiditic sequences deposited in the Chicontepec Basin. However, the former foredeep basin itself became subsequently uplifted and eroded, either during the Oligocene, or more likely during the Neogene times, its recycled material contributing also as a terrigenous source for younger clastic deposits in the offshore.

4.4. Fluid flow and hydrocarbon migration

As evidenced by the chemistry of fluid inclusions in cemented reservoirs and fractures as well as by the distribution of known hydrocarbon occurrences in the Cordoba Platform and adjacent Veracruz Basin, the regional fluid flow and petroleum systems were strongly affected in the vicinity of the southern section by these successive changes in the burial history and regional attitude of the basement.

Exhumed, biodegradated oil fields were described in the Tampico segment of the Sierra Madre Oriental (Pottorf et al., 1996, 1997).

Only heavily biodegraded dead oil (bitumen) was found locally in Coniacian–Santonian reservoir analogues cropping out in the central part of the Cordoba Platform, i.e. in the San José de Gracia anticline (Peñuela quarry; Fig. 3; Ferket et al., 2003; Ferket, 2004; Ferket et al., 2004, 2006), whereas both biodegraded and pristine oils have been produced in (dolomitized) Cretaceous platform limestones and in fractured slope breccias of the frontal duplexes, respectively at and below the Neogene unconformity (Prost and Aranda-Garcia, 2001).

The study of the paragenetic sequence of reservoir analogues and its relative chronology with respect to cemented fractures and burial-induced versus tectonic stylolites document also numerous episodes of paleo-fluid circulations, including hydrocarbons, but also meteoric water and Mg-rich mineralizing fluids, as well as local episodes of TSR (thermo-chemical-sulfate reduction), when early entrapped hydrocarbons interacted with evaporitic fluids (Fig. 11; Ferket, 2006).

Ultimately, this complex succession of tectonics, sedimentation and erosion processes and its incidence on the overall fluid flow, hydrocarbon generation and migration pattern were also simulated along the southern transect, using the 2D-Ceres basin modeling tool. Ceres is a prototype developed at IFP, which allows us for coupled thermal, fluid flow and petroleum modeling in tectonically complex areas. Ceres has been already applied in various compressional systems (Schneider et al., 2002; Schneider, 2003; Schneider et al., 2004). Results of this Ceres modeling are only briefly summarized here (fore more details, see Gonzalez-Mercado, 2007; Gonzalez-Mercado et al., 2008).

As already anticipated by former 2D-Thrustpack modeling (Ortuño et al., 1999, 2003), all the oil currently produced in the frontal duplexes is derived from the adjacent Veracruz Basin. Jurassic source rocks remained immature until the end of the Cordilleran orogeny. They entered subsequently into the oil window during Oligocene–Neogene episodes of increasing burial. Lateral migration toward the structural traps of the frontal duplexes was clearly enhanced by the progressive post-orogenic tilt of the basement (Fig. 12).

Two alternate hypotheses can be proposed to account for the dead oil found in the Peñuela reservoir analogue in the central part of the Cordoba Platform. In the first hypothesis, oil generated early in the

Fig. 8. A) Histogram of Th (homogenization temperatures) and Tm (temperature of last ice crystal melting) from fluid inclusions from the Cordoba Platform carbonates and B/C) results of PVT (Pressure–Volume–Temperature) modeling (after Ferket, 2006; Ferket et al., in press, in press-a, in press-b; modified).

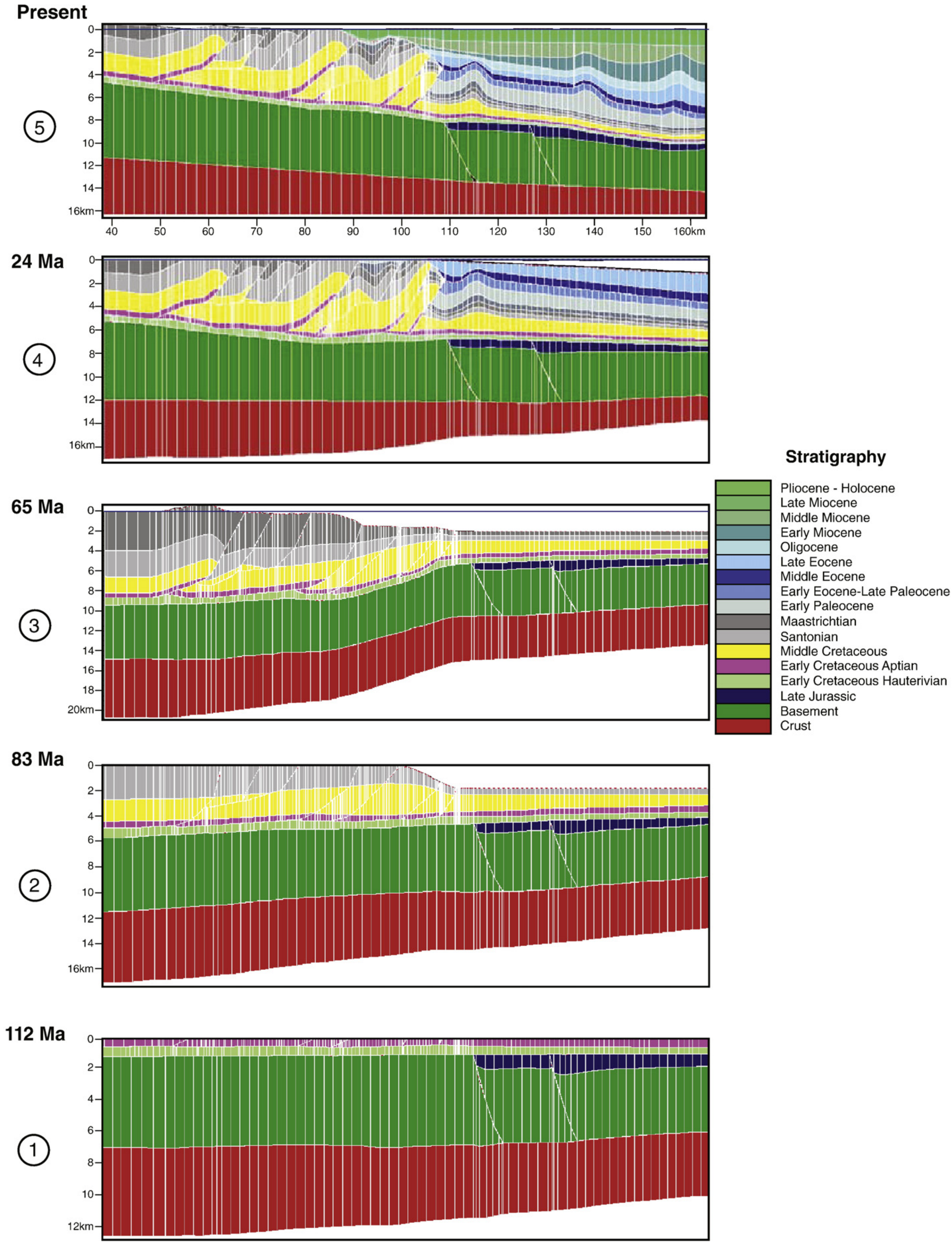

Fig. 9. 2D-Ceres serial cross-sections outlining the successive episodes of subsidence, uplift and tilting of the infra-Jurassic substratum along the southern transect (after Gonzalez-Mercado, 2007; Gonzalez-Mercado et al., 2008; modified).

Jurassic source rocks of the former Zongolica Basin in the west, synchronously with the foreland basin development, could have migrated eastward, being then trapped in the structural closure of the San José de Gracia anticline. The second hypothesis would favour a local, intraplatform source rock horizon within the Orizaba Formation. Subsequent erosion of up to 4.5 km of overburden resulted anyway in the destruction of shallower seals, interaction with meteoric water then inducing a strong biodegradation of the former oil pool. Due to the strong biodegradation, biomarker studies remain unconclusive on whether these hydrocarbon occurrences found quite far west of the thrust front indeed relate to a basinal source, or originated in a hypersaline lagoon.

5. Coupling kinematics and sedimentation in the offshore (Dionisos)

The offshore part of the northern transect was also used as a reference section for testing the ability of Dionisos sedimentary modeling tool to handle complex tectonics. Because we had no precise control on the present and past elevation and extend of the onshore source area for clastics, we did not work at all on the modeling of the erosion of the thrust belt and adjacent uplifted foredeep. Instead, we focused the study on the mode of marine transport and deposition across the margin, the calibration of seismic data against available wells data being sufficiently accurate to provide a good control on the volume of sediments deposited for each time interval. Only the main results of this study are summarized below (for more details on the litho-stratigraphic calibration and depth-conversion of the sections, see Alzaga-Ruiz, 2008; Alzaga-Ruiz et al., 2009a,b).

5.1. 2D forward kinematic modeling, vertical subsidence and quantification of the deformation

The first step of the kinematic modeling consisted in the unfolding of the structural section, thus providing a realistic geometry of the margin at the onset of the gravitational collapse, in Late Oligocene times. During this process, a special attention was paid to reconstruct the initial trajectory of future listric normal faults and spacing of future reverse faults.

This restored section was subsequently used as an input data for a Thrustpack forward kinematic modeling. Using a progressive trial and error process until the resulting section became consistent with the present-day structural section (Fig. 13), we applied simultaneously different types of deformation to the model:

1) Vertical subsidence of the basement, which is the main parameter controlling the accommodation space available for sediments and the overall paleo-bathymetric profile of the section;
2) Normal displacement along listric normal faults located in the western, near-shore part of the transect. Precise timing and amount of vertical offset along the main listric fault located near km 36 of the section were progressively adapted to fit with their final attitude in the present-day template.

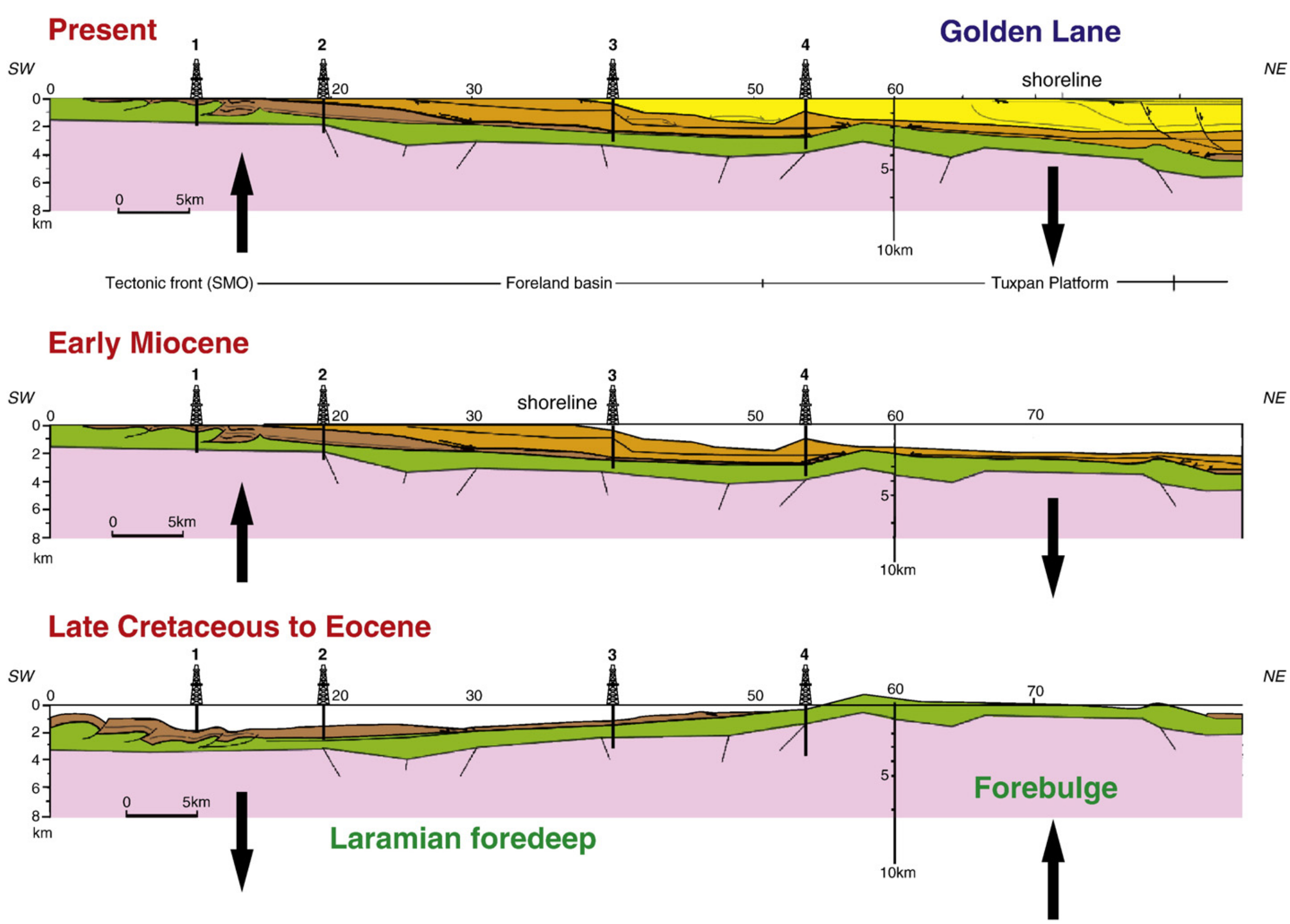

Fig. 10. Present and restored attitude of the basement of the Chicontepec Basin during the Laramide orogeny (after Alzaga-Ruiz, 2008; Alzaga-Ruiz et al., 2009a,b; modified).

3) Coeval reverse displacement was partitioned along both east-verging and west-verging thrust faults developing near the toe of the slope, in order to accommodate the lateral displacement along the basal detachment, with zero deformation east of km 108.

Synkinematic sedimentation was also applied to the model, the thickness of each stratigraphic interval being progressively adapted to fit with the present-day template.

5.2. Stratigraphic modeling and tectonic control on sandstone reservoir distribution

Although Paleogene paleo-canyons have been identified both north and south of the Golden Lane–Tuxpan Platform (Galloway et al., 1998; Fig. 1), and may have accounted for a direct transfer of sediments from the foothills to the abyssal plain, the studied section is located at a place where an emerged platform domain acted as an efficient barrier preventing the Chicontepec foredeep basin to communicate directly with the deep Gulf of Mexico Basin. Therefore, we did not attempt to simulate the transport and sedimentation of Paleogene series. As for the Thrustpack kinematic modeling, we started the Dionisos forward stratigraphic modeling from the Oligocene onward. The Dionisos software, developed at IFP, applies a 3D multi-lithologies diffusive model of transport (Granjeon, 1997; Granjeon and Joseph, 1999).

This forward stratigraphic modeling focused on the tectonic control exerted by the up-slope listric normal faults and compressional deformation operating at the toe of the slope on the overall distribution of debris flows, slumps and coarse sand clastics in the growth strata associated with active structures. The aim of this study was indeed to test the ability of stratigraphic modeling in predicting the distribution of potential reservoirs in stratigraphic traps developing between the shelf break and the toe of the slope, either in the vicinity of the roll-over or in isolated slope basins, but also in identifying during which time intervals coarse clastics were instead transferred directly from the shore to the deep abyssal plain.

Apart from the vertical and lateral deformations applied to the model to simulate both the subsidence and tectonic transport, the incidence of two other parameters has been carefully investigated during the Dionisos modeling:

1) The dipping attitude of the basement and average slope angle in the offshore part of the transect;
2) The velocity, density and charge of the water circulations.

Results have been plotted as a 3D block diagram, but also as 2D sections, both parallel and perpendicular to the shore, their direct comparison with interpreted 2D seismic profiles thus allowing us to

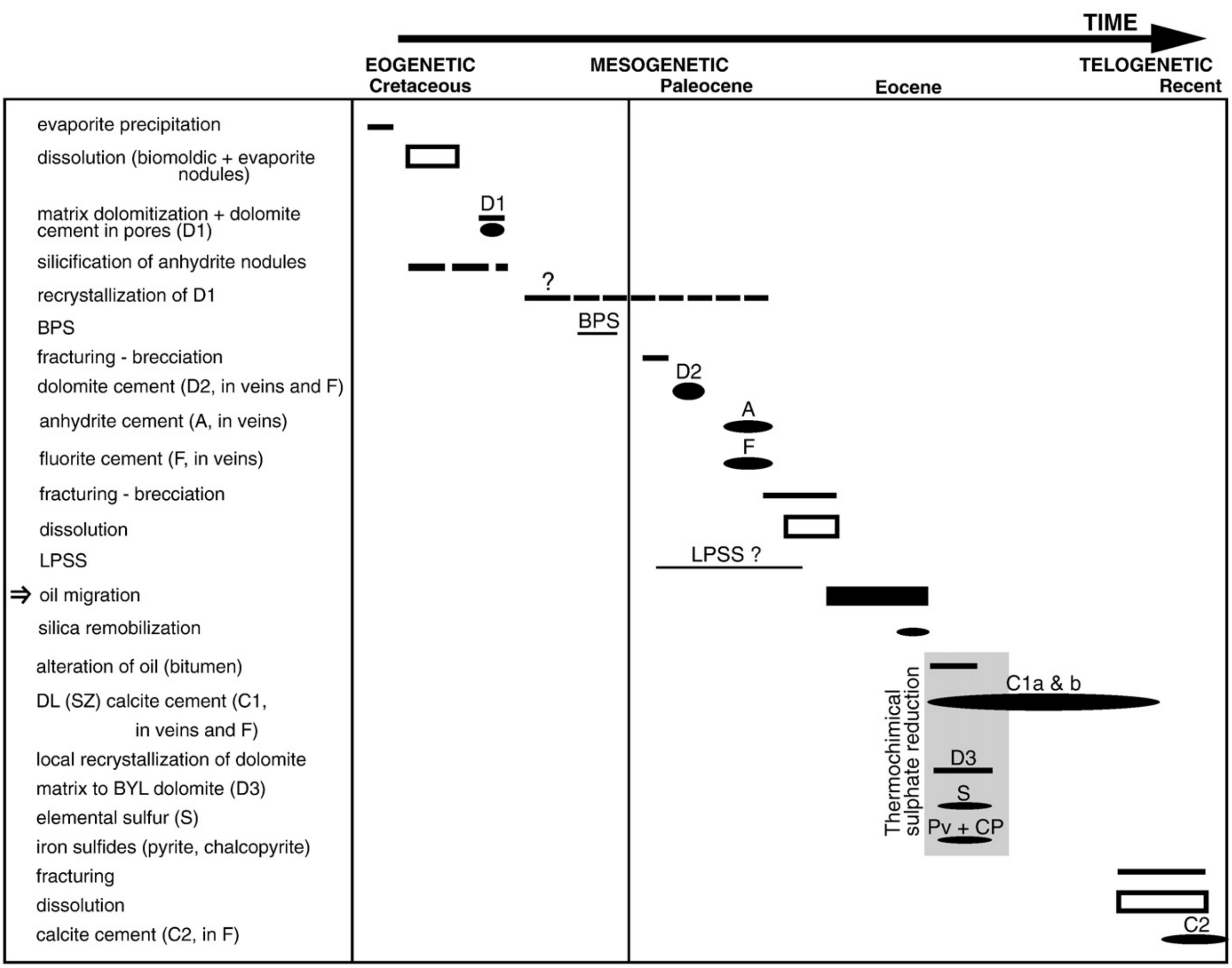

Fig. 11. Paragenetic sequence and chemistry of paleo-fluid circulations (after Ferket, 2006; Ferket et al., in press, in press-a, in press-b; modified). BPS: bedding parallel stylolitic planes; LPSS: layer parallel stylolitic peaks; D1 to D3: successive generations of dolomite; C1 and C2: successive calcite cements; P and CP: pyrite and chalcopyrite.

improve progressively the modeling by using again a trial and error process.

As evidenced in Fig. 13, the model predicts a localization of slump and debris flows near the footwall of the listric fault, whereas finer sand reservoirs can still be expected to account for stratigraphic traps in adjacent roll-over structures.

5.3. What is (are) the dominant parameter (s) inducing the gravitational collapse and overall architecture of the margin?

In the northern, north-western and southern margins of the Gulf of Mexico, the Jurassic salt distribution accounts directly for the localization of the basal décollement, at the base of the passive margin series, but also for shallower décollement horizons located within Cenozoic strata, at places where the salt was already tectonically injected and formed intercutaneous canopies. In the Veracruz offshore however no salt can be advocated to account for the architecture of the margin, nor for the development of the gravitational collapse of the slope. We shall discuss below the various parameters which may have contributed, either individually or jointly, to this collapse.

5.3.1. Sedimentary loading, ductile behavior of Eocene shales and overpressures

Seismic interpretation demonstrates that the main décollement level accounting for the gravitational gliding of the Neogene series is located within the Eocene strata, assumed to be made up of undercompacted shales. Although we did not address any coupled thermal, pore fluid pressure and petroleum modeling along this transect, we assume that the sedimentary load applied by Oligocene series was fast and large enough to generate overpressures in the underlying Eocene shales.

Alternatively, these Eocene shales had already a low friction angle, allowing them to behave as a ductile, mobile interface, which could have been activated as a décollement level as soon as the east-dipping attitude of the underlying brittle substratum became sufficient.

Although the entrance of source rocks in the oil window has also been advocated for the development of overpressure and gravitational collapse in other passive margins such as the Atlantic margin in Brazil (Cobbold et al., 2004), we do not believe this is the case here, because:

1) The burial of the Eocene series was probably not yet sufficient in Early Miocene to reach the oil window, unless we assume unrealistic high heat flow values;
2) There is no direct control yet on the distribution of organic-rich horizons across the margin, and we are not sure whether the Eocene series indeed constitute or not an effective source rock for hydrocarbons east of the Golden Lane (Holguin-Quiñones, 1988, 1991; Gonzalez and Holguin, 1992; Guzman-Vega, 1994; Guzman-Vega and Mello, 1994; Holguin et al., 1994; Guzman-Vega et al., 2001).

5.3.2. Shelf to slope break and localization of the listric normal faults

The lateral distribution of the load of the Oligo-Miocene overburden applied to underlying Eocene shales may account for the localization of the major listric faults, which actually initiated at the shelf break and prevented the shelf from any further progradation farther to the east (Wawrzyniec et al., 2004). A similar localization of listric faults at the shelf break has been observed in other passive

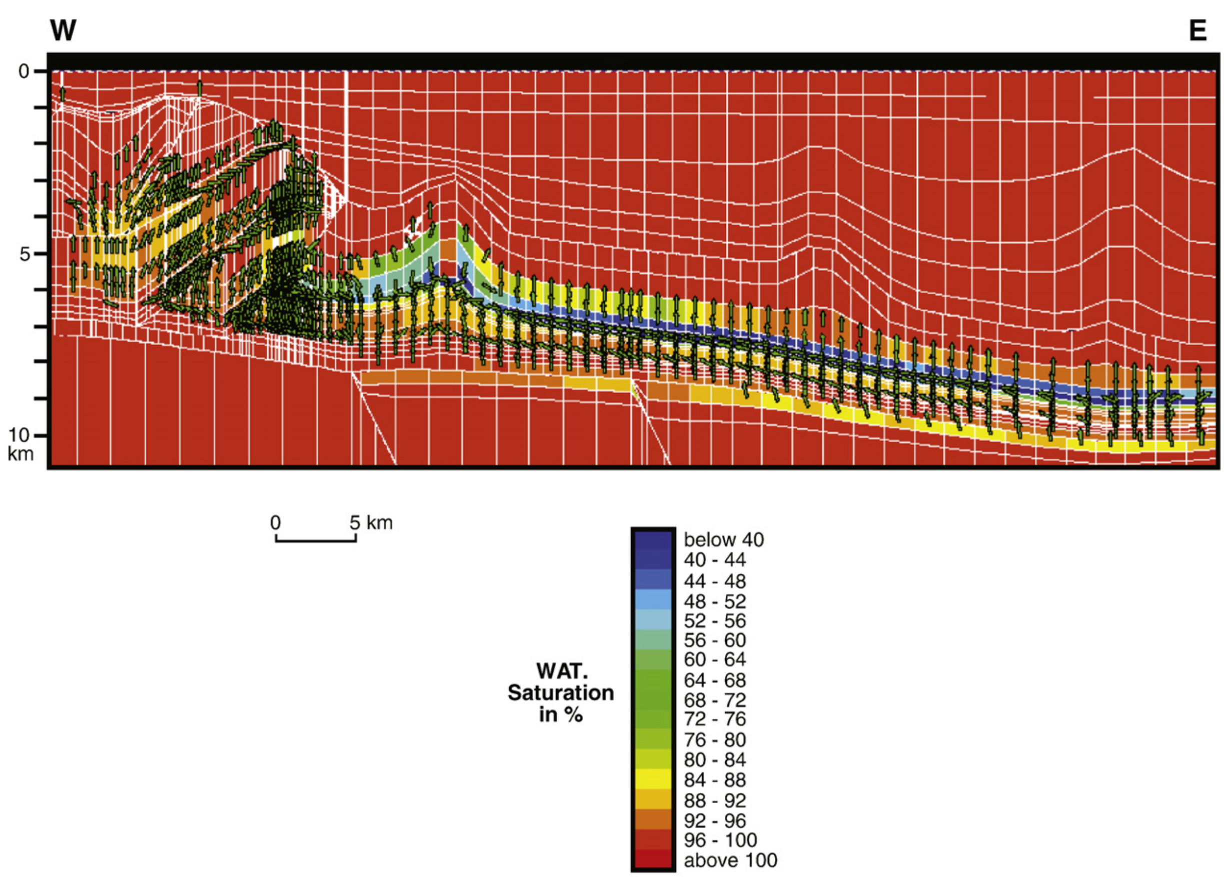

Fig. 12. Result section of the 2D-Ceres fluid flow and petroleum modeling across the Cordoba Platform and Veracruz Basin (southern transect; after Gonzalez-Mercado, 2007; Gonzalez-Mercado et al., 2008).

margin settings (Dailly, 1976; Crans et al., 1980; Coleman et al., 1983; Damuth, 1994). However, the main difference with other passive margins such as the south Australian margin, where ductile shales account also for the main décollement level, is the continuous growth observed here for the listric fault and associated half graben. In the southern Australian margin for instance, the shelf is prograding rapidly ocean-wards, after the main episode of gravitational collapse of the margin, most listric faults being sealed by the rapid progradation of the younger continental platform (Totterdell et al., 2000; Totterdell and Bradshaw, 2004).

5.3.3. Regional change in the basement attitude versus foreland inversion at or near the continent–ocean transition

The depth-converted structural section outlines also a drastic change in the dipping attitude of the basement beneath the intra-Eocene décollement level immediately east of the main listric faults (Fig. 6). This could relate to a Neogene transpressional reactivation of inherited basement structures at the ocean–continent transition, as already described recently (Le Roy, 2007; Le Roy et al., 2008).

5.3.4. West-verging versus east-verging attitude of the reverse faults

An abundant literature does exist, describing sand box experiments which compare quite well with the observed geometries of the Veracruz slope (Vendeville et al., 1987; Mourgues and Cobbold, 2006; and references therein). Smit et al. (Smit et al., 2003; Smit, 2005) published recently experiments which were initially built to mimic the mode of deformation, kinematics and continent-ward vergence of thrust faults observed in the deepest portions of the modern accretionary wedge developing off the Washington coast, in a purely compressional system. These experiments compare quite well with

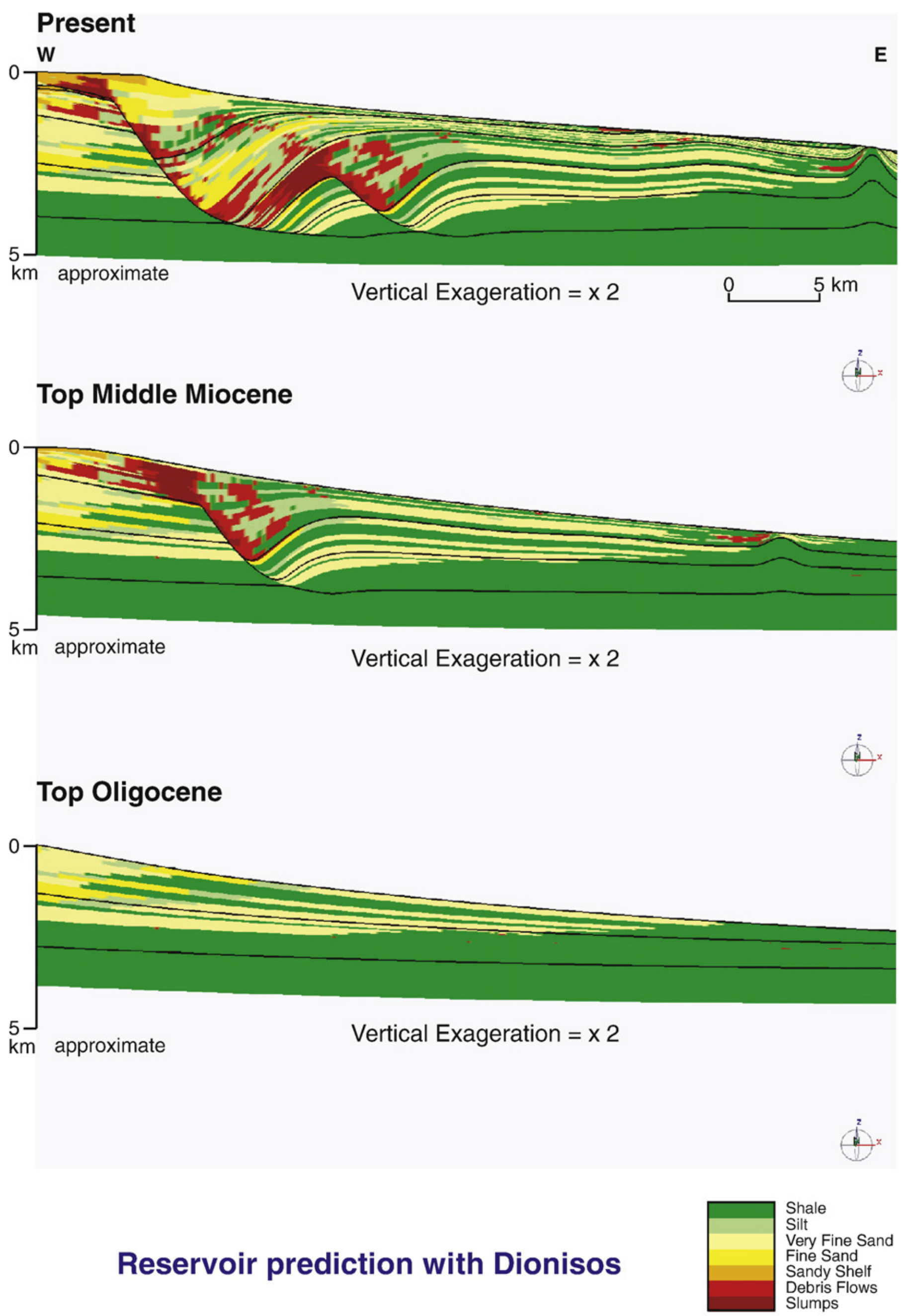

Fig. 13. Result section of the Dionisos stratigraphic modeling across the Veracruz offshore (northern section), outlining the tectonic control on the distribution of potential clastic reservoirs (after Alzaga-Ruiz, 2008; Alzaga-Ruiz et al., 2009a,b; modified).

the architecture of the deep water fold-and-thrust belt imaged on the Veracruz offshore section.

At this stage however, we are missing a direct stratigraphic calibration by exploration wells or dredging, to propose a relative chronology of the thrust sequence in this part of the section. At first glance, assuming that the thickness of synkinematic deposits in slope basins is directly indicative of their age, it sounds quite possible that individual folds and thrusts are indeed youngering eastward as in the sand box model. A counter-hypothesis remains however possible, assuming that the thickness of piggy-back slope basins (or mini basins, sensu Badalini et al., 1999) only relates to their distance to the main onshore source of clastics.

6. Post-Laramide mantle dynamics and its controls on shallow processes

The drastic change observed in the vertical motion and basement attitude of the Cordilleran foreland had direct implications on the regional surface processes such as the Cenozoic source to sink transfers, unroofing processes in the hinterland, as well as the depositional and gravitational evolution of the western slope of the Gulf of Mexico. Tilting of the basement controlled also the fluid flow dynamics and hydrocarbon migration in the Veracruz Basin and adjacent foothills of the Zongolica thrust belt. As discussed below, lithosphere and mantle dynamics must be advocated as one of the main forces controlling all these surface processes. In the following, we will thus enlarge the scope of the discussion, both vertically, by integrating the lithosphere architecture and its evolution through time, but also regionally, by extending the cross-section up to the Pacific Ocean in the west, and comparing the evolution of these Mexican transects to other segments of the North America Cordillera and adjacent foreland, both in the US and in Canada.

6.1. Timing of the Cordilleran orogen and development of the foreland flexure

The western margin of the North American craton changed from a passive margin configuration to an active margin during the Upper Jurassic, with the first docking of allochthonous paleo-oceanic and exotic volcanic arc terranes resulting in incipient foreland flexure and marine transgression in the Canadian foreland (Armstrong, 1974; Coney, 1978; Price, 1986, 1994; and references therein). Further tectonic loading occurred during the Lower Cretaceous, as accounted for by the main metamorphic ages of the Franciscan mélanges and coeval accretionary wedges in the west, extending from Baja California to Canada, and by an increase of subsidence rates in the Alberta foreland basin. However, the main contractional episodes of the east-verging Canadian Rockies did not start until the Late Cretaceous, and lasted only until the Eocene.

The tectonic agenda of the Zongolica and Sierra Madre Oriental thrust belts are quite similar with the deformation history of the Canadian Rockies and adjacent Canadian foreland. In the Cordoba Platform domain as well as in the Chicontepec Basin, the onset of the foreland flexure is well documented by the sinking of former platform domains and the onset of siliciclastic sedimentation during the Late Cretaceous. Timing of thrusting is also dated as Late Cretaceous to Eocene in age.

6.2. Regional evidence for post-orogenic unroofing and uplift of the North American Cordillera

No synkinematic piggyback sediments were preserved in the Canadian Rockies nor in the Sierra Madre and Zongolica thrust belts, because of the large amount of synorogenic and post-orogenic erosion. As indicated earlier, up to 4.5 km of overburden were removed locally from the Cordoba foothills since the onset of the deformation. Large amounts of post-Laramide erosion is also evidenced farther north in Mexico on seismic profiles in the inner part of the Chicontepec Basin, or by means of Apatite Fission Tracks in the Sierra Madre Oriental and Burgos Basin area.

Regional erosional profiles computed by inversion of maturity data (Tmax and Ro) along Canadian transects indicate that the amount of post-Laramide erosion is quite large, even in the autochthonous foreland. For instance, up to 4 km of Late Cretaceous to Eocene flexural sequences have been removed by erosion since the end of the Laramide orogeny in the vicinity of the tectonic front, west of Calgary, decreasing progressively toward the east with still an average value of 1.8 km of post-Laramide erosion at 100 km east of the thrust front.

Amount of erosion became even larger in the foothills, in excess of 8 km in the Canmore coal basin which is currently located at 60 km west of the thrust front, but a large part of this erosion could be synkinematic, rather than post-Laramide as in the foreland (Faure et al., 2004; Hardebol et al., 2007).

Another indicator of post-orogenic foreland uplift is provided by the current elevation of Calgary, which is currently located within the autochthonous foreland, but yet at 1 km above the sea level.

6.3. Subduction of the Pacific oceanic lithosphere, coeval mantle dynamics beneath the North American craton and its incidence on surface topography

Anomalous positive topography and post-orogenic extensional collapse have been documented in the hinterland of the North American Cordillera, from Canada to Mexico, accounting for the peculiar development of the Basin and Range province, at its best development in the US, and to the Cenozoic exhumation of the lower

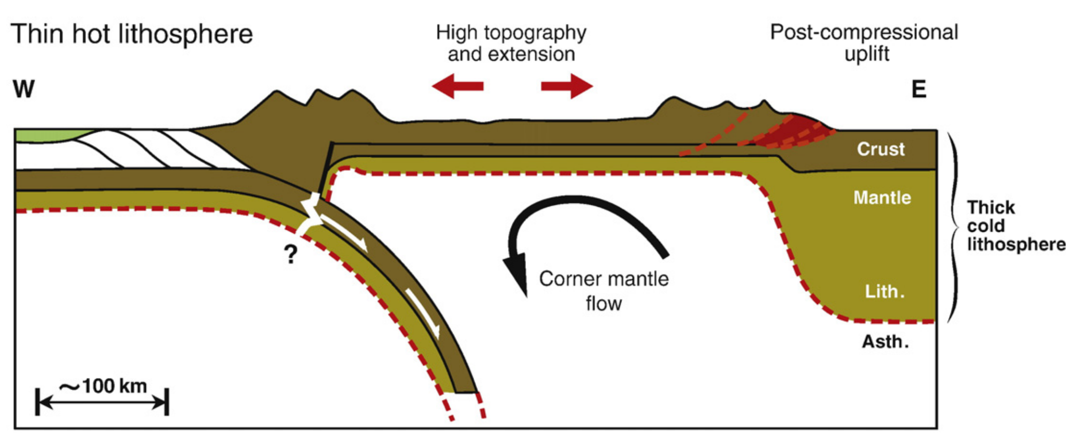

Fig. 14. Sketch outlining the current lithospheric architecture of a transect from the Pacific Ocean to the Alberta Basin (after Clowes et al., 1995; Hyndman et al., 2005), outlining the interactions between deep processes such as subduction and mantle convection, and shallower processes, such as crustal uplift, large wavelength basement folding and erosional unroofing.

continental crust in numerous core complexes, both in Canada and the US (Gans and Miller, 1993).

Recent transcontinental geophysical surveys such as LITHOPROBE (Canada) and COCORP (US) have provided direct control on the present architecture of the crust and lithosphere along regional transects crossing the North American Cordillera from its foreland in the west, up to the Pacific Ocean in the west (Price, 1986; Beghoul, 1991. Clowes et al., 1995; Hawkesworth et al., 1995; Zandt et al., 1995; Karlstrom, 1998; Keller et al., 1999; Hyndman and Lewis, 1999; Goes and van der Lee, 2002; Hammond, 2004; Hammond and Thatcher, 2005; Hyndman et al., 2005; Currie et al., 2007; Hammond et al., 2008). More speculative sections have also been proposed in Mexico (Gombey et al., 1989; Ortega-Gutierrez et al., 1990; Spranger, 1994; Barboza, 1995).

The common picture of all these lithospheric-scale sections is the incidence of the subduction of the Pacific oceanic lithosphere and progressive downward deviation of this subducting slab on the overall mantle dynamics and advection of heat inducing dynamic topography in the hanging-wall (Fig. 14; Liu and Shen, 1998; Lowry et al., 2000; Artemevia, 2003; Hyndman et al., 2005), resulting in:

1) A progressive thinning of the mantle lithosphere beneath the former Cordilleran edifice;
2) Heating and ductile flow in the lower crust;
3) Thermal doming, uplift and coeval extensional collapse of the brittle upper crust.

As evidenced by the erosional profiles in the Canadian foreland and the basement architecture of these two Mexican transects, the surface wave length of the uplifted and unroofed domain impacted by these deep mantle processes extends widely across the former Laramide thrust front, as far east as the western margin of the Gulf of Mexico.

6.4. What is the fate of erosional products of the Cordillera? Its link with the Cenozoic siliciclastic infill of the Gulf of Mexico and gravitational collapse of its northern and western margins

From Canada to Mexico, it is easy to trace the present-day pattern of erosional products of the North American Cordillera, which is controlled by the topography, distribution and extent of the main rivers drainage and continental divides (Fig. 15). As it stands, sediments derived from the unroofing of the hinterland of the Cordillera, i.e. from the Coast Ranges to the Basin and Range Province and coeval extensional provinces, are dominantly transferred directly to the Pacific Ocean, or, via the Colorado River system, to the Gulf of California. In Mexico, the frontal units of the thrust belt (Sierra Madre Oriental) constitute a major source for the clastics which are transferred to the Gulf of Mexico. Farther north, the eastern Cordilleran foothills and adjacent foreland can be subdivided in two distinct segments, because the present-day continental divide between the Arctic related-drainage system and the Mississippi River system, which flows towards the Gulf of Mexico, is grossly located along the political boundary between Canada in the US. However, not all the sediments transported to the Gulf of Mexico are presently coming from the Cordillera, part of them instead being derived from the rejuvenated topographies of the Appalachian system.

Capturing instant pictures of the drainage areas of the main river systems from Late Cretaceous onward sounds much more complicated. However, attempts have already been made by Galloway et al. (1998, 2000) and Galloway (2005) to map both onshore and offshore the regional extent of source to sink transfer systems, with long-living paleo-rivers such as the Eo-Rio Grange or Eo-Mississippi rivers. Worth to notice, Quaternary ice sheets and related loading, as well as subsequent ice retreat and unloading have greatly impacted the recent history and northern extent of the Mississippi River drainage (see Galloway's tentative maps for the Miocene and Ice time, to be compared with present drainages; Galloway, 2005).

Although the river systems coming from the Sierra Madre Oriental and Zongolica thrust belt are much shorter than the Rio Grande and Mississippi rivers, post-Laramide erosional products of the Mexican Cordilleran domain have widely contributed to rapidly increase the sedimentary load applied to Eocene shales, resulting in pore fluid pressure building in the future décollement horizon, and inducing the subsequent gravitational collapse of overlying Oligo-Miocene siliciclastic deposits of the western margin of the Gulf of Mexico from Early Miocene onward.

Although the basal décollement is made up of Jurassic salt in the other, northern and north-western segments of the margin of the Gulf of Mexico, we believe that the post-Laramide erosional products of the

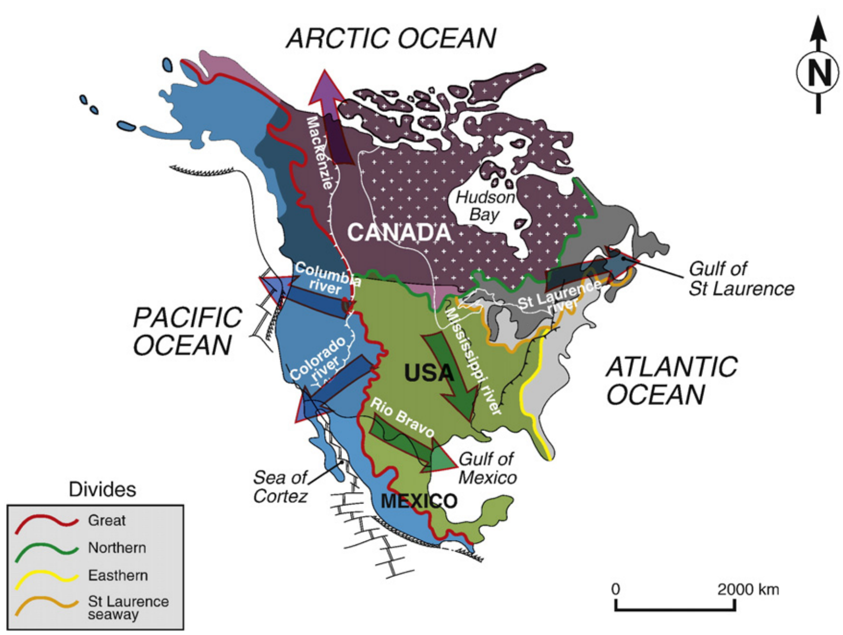

Fig. 15. Physiographic map of North America and the Gulf of Mexico, indicating the current continental divides and the main Neogene depocenters, to be compared with Cordilleran and adjacent uplifted foreland which contributed as source areas for the clastics (after http://en.wikipedia.org/wiki/continental_divide; http://worldatlas.com/aatlas/infopage/contgiv.htm).

Cordillera and adjacent uplifted foreland have also largely contributed there to increase the sedimentary load, resulting in the generalized gliding of the slopes.

7. Discussion and perspectives

Regional structural transects extending from the Cordilleran foothills in the west to the deep abyssal plain of the Gulf of Mexico in the east outline a major post-Laramide tilt of the basement, which is presently dipping towards the east beneath the Cordoba Platform (southern section) and Chicontepec Basin (northern section). Paleo-thermometers help to estimate the thickness of eroded sediments in the foothills and adjacent foreland, and to restore a west-dipping attitude of the foreland basement at the time of the Cordilleran orogeny, accounting for a classic foredeep configuration.

Mantle dynamics at the rear of the Pacific subduction are advocated as the engine of such post-orogenic bending and uplift of the lithosphere, which is observed all along the North American Cordillera, from Mexico to Canada. This post-Laramide vertical motion of the basement resulted in a rapid and massive unroofing of the foothills and adjacent foreland. Post-Eocene erosional products were transferred rapidly to the western margin of the Gulf of Mexico, where they contributed, by increasing the sedimentary load, to a destabilization and gravitational gliding of the entire Cenozoic sedimentary wedge.

Neogene transpression, basement inversion and/or buckling operating near the continent–ocean transition probably accelerated the gravitational process by increasing the dipping attitude of the basement beneath the main décollement level.

The petroleum reservoirs of the Sierra Madre Oriental and the Peñuela reservoir analogue in the central part of the Cordoba Platform were mostly exhumed and biodegraded during and after the Cordilleran orogeny (Pottorf et al., 1996, 1997; Yurewicz et al., 1997; Ferket, 2004; Ferket et al., 2000, 2003). However, the younger petroleum systems of the eastern front of the Cordoba Platform and Veracruz Basin have been also strongly affected by this recent deformation and tilting of the foreland basement, resulting in a unique migration pattern, whereby hydrocarbon products generated in the foreland during post-Laramide times migrated towards the adjacent foothills domain and then inactive thrust front.

Reservoir development in Cretaceous platform carbonates in the Golden Lane and other platform domains was widely affected by interactions with meteoric water in the forebulge area, but also in the foothills, where huge erosion occurred (Enos, 1977a,b, 1985, 1988; Ferket, 2004, 2006; Ferket et al., 2000, 2003, 2004 and 2006).

Near the Veracruz–Cordoba thrust front, the Campanian slope breccias of the San Felipe Formation have been described as a fracture-dominated limestone reservoir. However, many other slope breccias in Mexico have developed a rather vuggy porosity, i.e. in the Cantarell field in the offshore, and display evidence for both hydrothermal dolomitization and dissolution. Because the current Ceres modeling suggests that large post-Laramide upward transfers of basinal fluids (hot and Mg-enriched) occurred from the Veracruz Basin towards the frontal duplexes, it would be worth looking there again in these Cretaceous slope breccias for the possible occurrence of saddle dolomite and vuggy porosity.

Additional Ceres modeling would be required along the offshore part of the northern section in order to reconstruct properly its pore-fluid pressure evolution. Further Dionisos stratigraphic modeling should also be extended to a wider portion of the Gulf, in order to take into account more distal, either northerly or southerly sources of clastics such as the Rio Grande and other large rivers, as they may have contributed to feed more clastics in the deep abyssal plain.

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