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The Moín High, East Costa Rica: Seamount, laccolith or contractional structure?

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ABSTRACT

The back-arc area of the southern Central American arc–trench system in East Costa Rica is characterized by a complex basin system. An extensional back-arc area (the North Limón Basin) and a compressional retro-arc foreland basin (the South Limón Basin) are closely related. Both basins are separated by an approximately 50 km long and 30 km wide mound-shaped structure referred to as Moín High, which evolved in Eocene times. The Moín High has previously been interpreted as a basement structure or paleo-high. The modern geothermal gradient is 3 °C/100 m. There is no evidence for thermal anomaly or higher heat flow in that area. A mean heat flow of 56–60 mW/m^2 implies that an origin as a volcanic seamount or magmatic intrusion is unlikely. 3D static models show that the Moín High trends NNE–SSW and has an antiformal shape in cross-section and an elliptic outline in map view. The trend of the Moín High coincides with the orientation of folds in West Costa Rica that formed in response to an Eocene deformation phase. The seismic lines show that Miocene reflectors onlap against the structure. Based on this data set it is likely that the Moín High is an anticline formed due to contraction.

1. Introduction

The Limón back-arc basin extends along the Caribbean Coast of Costa Rica. In the central and northern part of this basin large mound-shaped structures occur (Fig. 1), which have been interpreted as basement structures (Sheehan et al., 1990) or paleo-highs (Barboza et al., 1997). One of these structures is referred to as Moín High, which is located close to the present-day coastline north of Puerto Limón, next to the Trans Isthmic Fault System at the boundary of the undeformed North Limón Basin and the deformed South Limón Basin. The Moín High evolved in Eocene times (Barboza et al., 1997), has an elliptic outline in map view and represents a four-way dip closed area. In general such a structure is an interesting exploration target because it can retain oil and gas. In the past the Limón Basin was regarded as prolific hydrocarbon province and several wells were drilled (e.g., Sheehan et al., 1990; Barboza et al., 1997; Petzet, 1998). Archer et al. (2005) showed the importance of a careful and multi-disciplinary examination of such a structure to avoid a misinterpretation and to minimize the risk for hydrocarbon exploration. Based on the shape and outline, there are different possibilities to explain the evolution of the Moín High: (1) a volcanic seamount, (2) a magmatic intrusion, (3) a salt pillow/diapir, (4) an uplifted basement block, (5) an inversion structure or (6) an anticline (Fig. 2). Seismic sections and well data made available by the Costa Rican Ministry of Environment and Energy (MINAE) allow a detailed reconstruction of the geometry and temporal evolution of the structure. Pre-growth, growth and post-growth strata was analysed to reconstruct the uplift history of the Moín High. The combination of seismic lines, well data, 3D static models and basin modelling techniques helps to verify the different possibilities for its mode of origin.

2. Geological setting

The geology of Central America is characterized by the interaction of five lithospheric plates, namely the oceanic Cocos, Nazca and Caribbean Plates and the continental North and South American Plates (Fig. 3a). Tectonics processes in this region are dominated by the subduction of the Cocos and Nazca Plates beneath the Caribbean Plate along the NW–SE trending Central America trench. The present-day subduction velocity off Costa Rica, relative to the Caribbean Plate, is 8.5 cm/yr (DeMets, 2001). The Central American subduction zone is characterized by strong along-trench variations in the dip angle of the Wadati–Benioff zone. Protti et al. (1995) observed an angle of 84° under Nicaragua, 60° under Central Costa Rica and a flat slab with no Wadati–Benioff zone under South Costa Rica. The Central American land-bridge above this subduction zone is a complex assemblage of distinct crustal blocks (Fig. 3a) including, from NW to SE, the Maya, Chortis, Chorotega and Choco Blocks (Donnelly, 1989; Weinberg, 1992; Di Marco et al., 1995; Campos, 2001). The Maya and Chortis Blocks have a continental basement, whereas the Chorotega and Choco Blocks comprise island-arc segments underlain by Mesozoic oceanic crust

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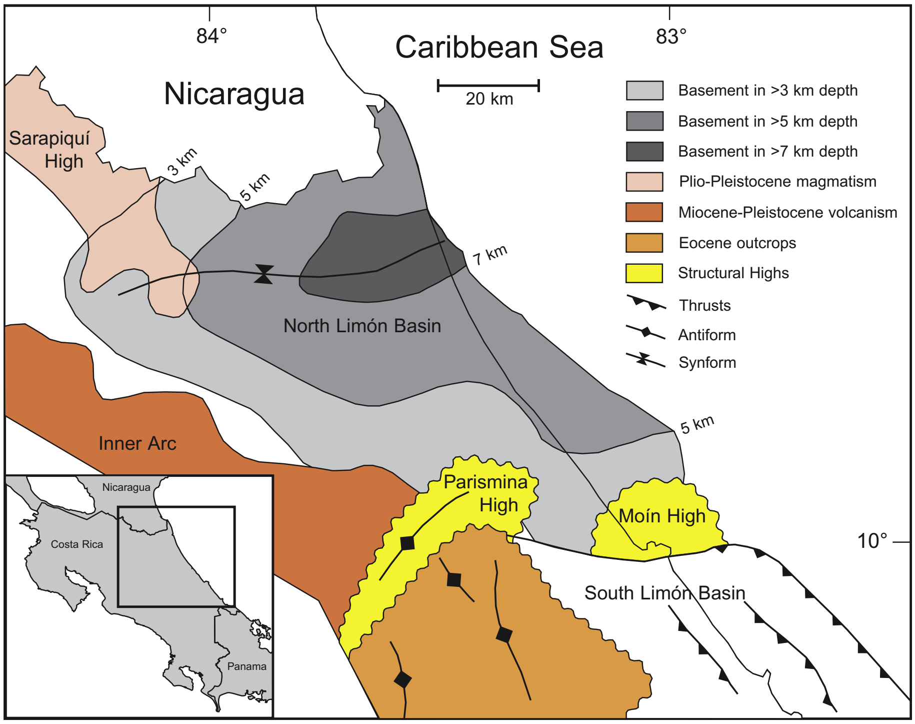

Fig. 1. Map of the Costa Rica back-arc area, showing main faults, structural highs and sediment thickness (based on Barboza et al. (1997)).

(Escalante and Astorga, 1994). The Chorotega Block, which represents the Costa Rican part of the island-arc, can be subdivided into a northern and a southern arc segment (Seyfried et al., 1991). The northern arc segment is bounded to the north by the Hess Escarpment and to the south by the Trans Isthmic Fault System (Fig. 3b). The Hess Escarpment is a NE–SW trending bathymetric feature in the Caribbean Sea, which separates the continental Chortis Block from the oceanic Colombia Basin (Krawinkel and Seyfried, 1994; Campos, 2001). The Hess Escarpment has been interpreted as an Upper Mesozoic Plate boundary, acting as a strike-slip zone to compensate the movements between the Chortis and Chorotega Blocks and the Caribbean Plate (Krawinkel, 2003). The Trans Isthmic Fault System is an E–W trending active lineament. It shows mainly sinistral movements (Krawinkel and Seyfried, 1994; Krawinkel, 2003). The southern Costa Rican arc segment is located south of this lineament and belongs to the Panama Microplate.

The Limón back-arc basin is situated beneath the present-day coastal plain and continental shelf of eastern Costa Rica (Fig. 3b) (Weyl, 1980). Its northern boundary is the Hess Escarpment, to the west and south the basin is bounded by the volcanic arc. The eastward extent is defined by the 200 m bathymetric contour line of the Caribbean Sea in the north and by the extent of the Limón fold-and-thrust belt in the south (Fig. 3b). The Limón Basin can be subdivided into a northern and a southern sub-basin, separated by the Moín High and the Trans Isthmic Fault System (Fig. 3b). The Moín High is located north of Puerto Limón (Fig. 3c). The North Limón Basin belongs to the North Costa Rican arc segment, and in contrast to the South Limón Basin, is undeformed. The North Limón Basin is filled with up to ~7 km of Upper Cretaceous to Recent deep-marine and continental volcaniclastic rocks and limestones (Sheehan et al., 1990; Bottazzi et al., 1994), and still undergoes subsidence today (Mende, 2001). The South Limón Basin, located on the South Costa Rican arc segment, is filled with up to ~8 km of Upper Cretaceous to Recent deep-marine to continental volcaniclastic rocks (Sheehan et al., 1990; Coates et al., 1992, 2003; Amann, 1993; Bottazzi et al., 1994; Fernandez et al., 1994; McNeill et al., 2000; Mende, 2001; Campos, 2001). Deposition of carbonates occurred during Late Cretaceous, Eocene and Oligocene times (Fig. 3d). In southern Costa Rica conditions change from steep low stress subduction to flat high stress subduction. The island-arc shows a deformed and uplifting fore-arc and back-arc area, separated by the Talamanca Range with a height of 3.8 km and a width of 60 km. In the Talamanca Range the highest peaks of southern Central America occur, but there are no active volcanoes in that region. The back-arc is dominated by the Limón fold-and-thrust belt (Barboza et al., 1997). The internal part of this fold-and-thrust belt is characterized by thick-skinned tectonics. Deep earthquake loci provide evidence for active, deep seated thrusts (Suárez et al., 1995). In contrast, the external part of the Limón fold-and-thrust belt adjacent to the Caribbean Coast is dominated by thin-skinned tectonics. Seismic reflection lines show that all thrusts sole into a common detachment at a depth of 3.7–4 km (Brandes et al., 2007). Since the Middle Miocene the fill of the onshore South Limón Basin was affected by intense folding and thrusting (Campos, 2001). Recent earthquake activity indicates ongoing deformation in this region (Protti and Schwartz, 1994; Suárez et al., 1995).

3. Database and methods

The data used in this study include a grid of 2D seismic reflection lines, comprising NE–SW directed in-lines and NW–SE directed cross-lines (Fig. 3c). The seismic lines were acquired during onshore and offshore seismic campaigns in the 1970s and 1980s. Stratigraphic and lithologic control for the seismic interpretation is derived from one onshore well (Well 1). This well penetrates Pleistocene to Eocene sandstones, shales and limestones. Data from a second offshore well (Well 2) were also integrated. Seismic interpretation was performed with the software package Kingdom Suite©. The seismic interpretation was used as a basis for the 3D interpretation of the Moín High and the surrounding basin-fill. Key seismic reflectors (base Middle Miocene, base Late Miocene, base Pliocene, base Quaternary and sea-floor) were identified and

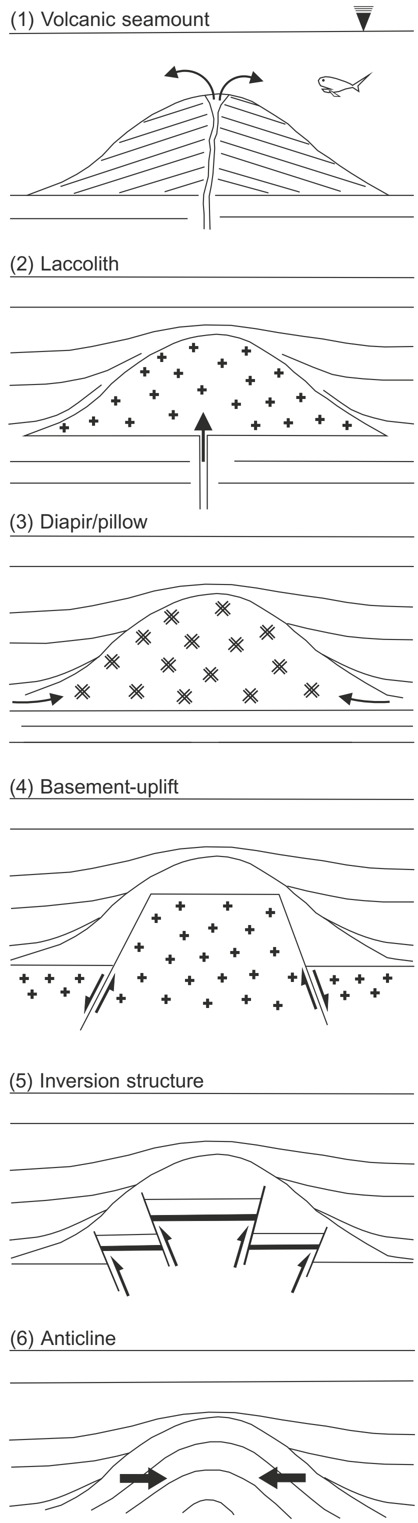

Fig. 2. Different modes to explain the evolution of the Moín High: (1) a volcanic seamount, (2) a magmatic intrusion, (3) a salt pillow/diapir, (4) an uplifted basement block, (5) an inversion structure or (6) an anticline structure.

mapped in detail throughout the study area. 3D static models were created to visualize the geometry of the Moín High. From the seismic data it was also possible to identify different deformation phases, which can be correlated with the deformation phases that had previously been recognized in the onshore area of Costa Rica. Basin modelling was carried out with the software PetroMod© 1D to reconstruct the burial history of the Moín High. A depth conversion was performed on the basis of interval velocities to infer the real geometry of the structure.

4. Seismic interpretation and well data

Several seismic lines allow insight into the Moín area (Fig. 3c). Well 1 was drilled onshore, north of Puerto Limón on the northern flank of the Moín High close to the present-day coastline and provides the necessary stratigraphic and lithologic control for the seismic interpretation. On the seismic sections, the Moín High has a mound-like, antiformal shape. The length of the structure is approximately 50 km, the width is approximately 30 km. The southern flank is steeper than the northern one. The seismic line (a), shown in Fig. 4a) displays a package of strong reflectors, which separates the Moín High from the surrounding and overlying sedimentary rocks. Especially the upper reflectors are very distinct and continuous. The reflector package has a constant thickness even on the crest of the structure. Below this reflector package the Moín High shows a weakly layered reflector pattern with single slightly stronger reflectors, which are not continuous. The central part of the structure is characterized by a very diffuse reflector pattern. There is no reliable information for these parts of the Moín High and the presence of artefacts can not be ruled out. On the seismic section (b) shown in Fig. 5 the reflector package on the northern flank of the structure is less distinct, but a set of strong reflectors are present, which delineate the Moín High from the surrounding and overlying sedimentary rocks. These strong reflectors may result from an increase in the acoustic impedance. Data quality of the in-lines is limited and the internal structure is not visualized very well on these sections. A small graben structure is visible in the crestal area of the Moín High (Fig. 4b). The fill of the North Limón Basin is characterized by laterally continuous reflectors, which can be traced along section (b) (Fig. 5). These reflectors form packages with a constant thickness. The individual packages are bounded by high amplitude reflectors. Some of the high amplitude reflectors can be correlated with lithological changes. The strong reflector at 2.3 s in Fig. 4a) corresponds to a change from shale to limestone at the boundary Early Miocene–Middle Miocene in Well 1.

Well data in combination with the seismic lines provide important information about the temporal evolution of the Moín High. Well 1 penetrates Pleistocene to Middle Eocene sandstones, shales and limestones (Fig. 4). The terminal depth is 3356 m. At a depth of 2910 m Middle Eocene limestones are directly overlain by Lower Miocene limestones. Upper Eocene and Oligocene deposits are absent. The interpreted time gap is at least 15 Ma. Early Miocene and Early Middle Miocene deposits show a clear onlap against the Moín High. This is indicated by several onlapping reflectors (Figs. 4b and 5). Late Middle Miocene and Late Miocene reflectors drape the Moín High. The wedging of reflector packages against the Moín High implies that the missing Upper Eocene and Oligocene units are present in the deeper parts of the basin. The unconformity on the flank of the Moín High is interpreted as a local feature, it is not present in the deeper parts of the basin. Middle Miocene and Pliocene to Lower Pleistocene deposits show an increased thickness above the crestal graben structure.

The depth converted section without vertical exaggeration displays the true geometry of the Moín High (Fig. 4d). After the depth conversion, the structure has a much lower relief than on the seismic section in two-way-travel time, but the convex shape is still present.

From the seismic lines, 3D static models were created. These models clearly show that the structure has an elliptic outline and trends NNE–SSW (Fig. 6a). An axis can be reconstructed that plunges towards NNE. In plan view the Moín High is elongated. The northwest and southeast flanks are steep compared to the

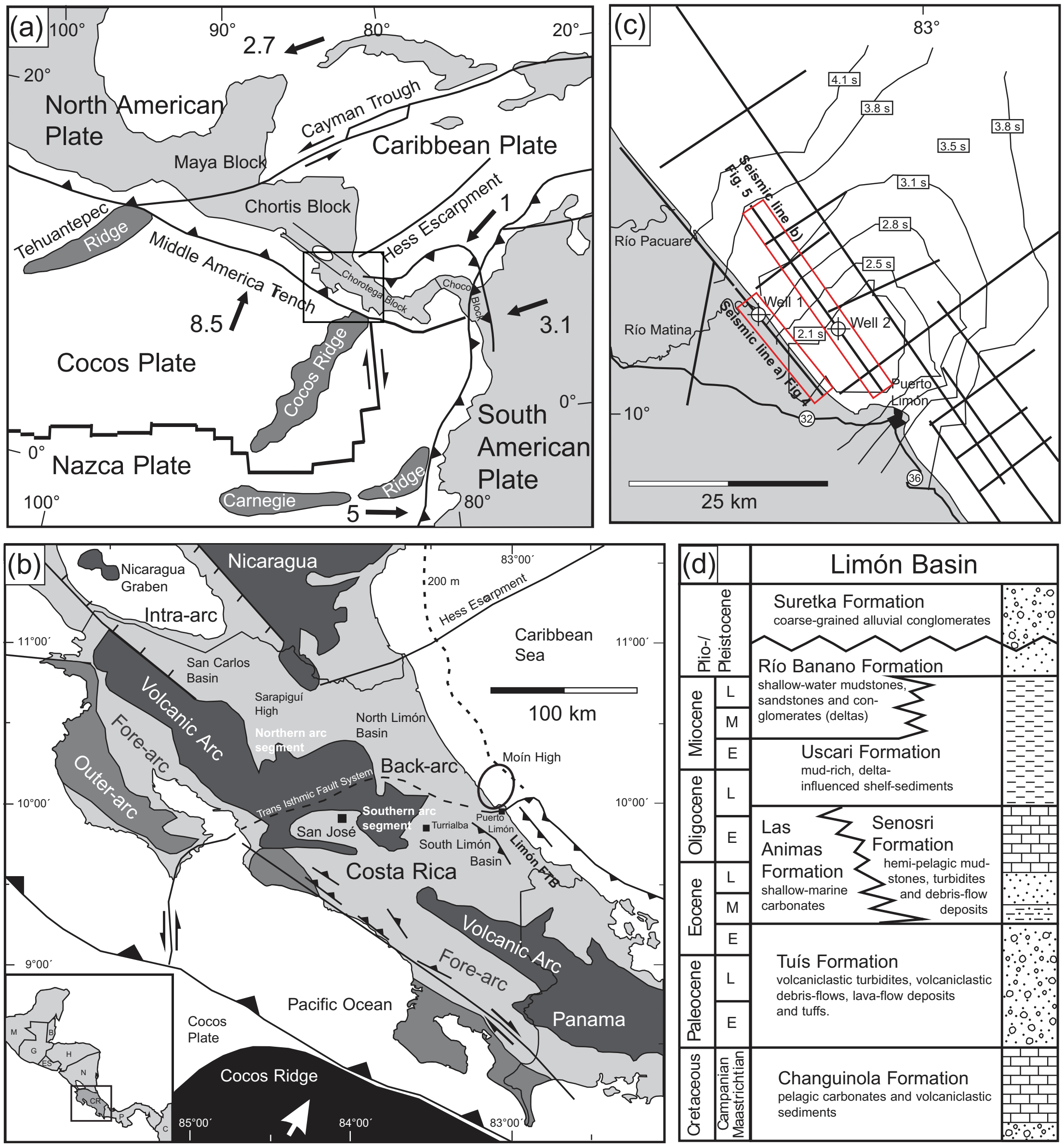

Fig. 3. (a) Plate tectonic setting of the Caribbean region (modified after Ross and Scotese, 1988; Donnelly, 1989; Meschede and Frisch, 1998). (b) Geological map of Costa Rica. The Moín High is situated at the Caribbean Coast (modified after Barboza et al., 1997; Fernandez et al., 1997; Campos, 2001). (c) Seismic grid of the study area. The red boxes indicate the seismic sections shown in Figs. 4 and 5. (d) Stratigraphy of the Limón Basin (modified after Mende, 2001). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

gently dipping northeast one. Due to the lack of onshore data the southwestward extent of the structure is unknown.

5. Basin modelling

Basin modelling is a numerical method to simulate the complex processes, which occur during the formation and evolution of a sedimentary basin (Hermanrud, 1993). The term basin modelling is mainly used for reconstructing the burial history and temperature evolution of a basin (Poelchau et al., 1997). The basin modelling part of this project was carried out with the software PetroMod® 1D, which was developed by the IES GmbH, Germany. PetroMod® allows to study the burial history and temperature evolution of a sedimentary basin.

A basin modelling study with PetroMod® follows a standard workflow. At first a conceptual model must be created, which is based on the results of a basin analysis. The conceptual model is the description of the geologic evolution of a basin (Poelchau et al., 1997). For such a conceptual model the complex real system must be simplified and reduced to a few fundamental parameters (Welte and Yükler, 1981). The depositional history of the basin is divided into distinct events. Each event can represent a phase of deposition, non-deposition or erosion. It is necessary to reconstruct the complete evolution of a sedimentary basin. Therefore episodes of non-sedimentation or even erosion must be quantified (Poelchau et al., 1997). Absolute ages and, in a second step, lithologies must be assigned to each event. The absolute age is important to reconstruct the temporal evolution.

In this study basin modelling was performed to reconstruct the burial history of the Moín area. The input for the simulation is derived from Well 1. The most important input parameters are the age and thickness of the sediments as well as their lithology. The age is important to reconstruct the temporal evolution. The lithology determines the behaviour during compaction. The geohistory

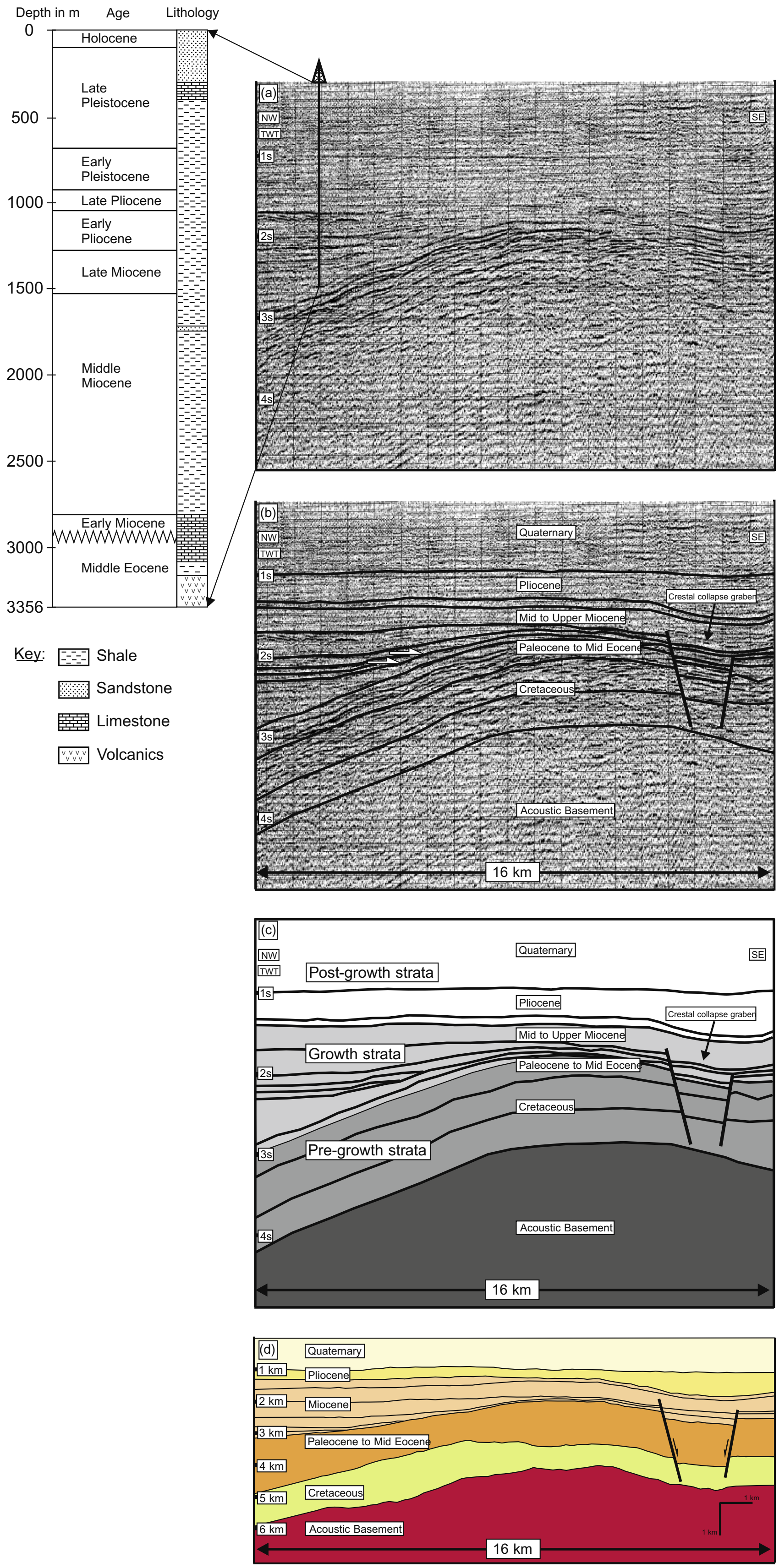

Fig. 4. (a) Seismic section and well data of Well 1. The section is 16 km long and trends NW–SE. It covers parts of the northwestern flank and the crest of the Moín High. (b) Interpreted section showing the convex Moín High with the onlapping reflectors. A pronounced graben is visible on top of the Moín High. (c) Seismic section subdivided in pre-growth, growth and post-growth strata. The growth strata have a distinct wedge-shaped geometry. (d) Depth converted version of seismic line. The section has no vertical exaggeration and displays the true geometry of the Moín High. After the depth conversion, the structure has a much lower relief than on the seismic sections in two-way-travel time, but the convex shape is still present. The thickness variations in the Cretaceous unit are probably an artefact from the depth conversion.

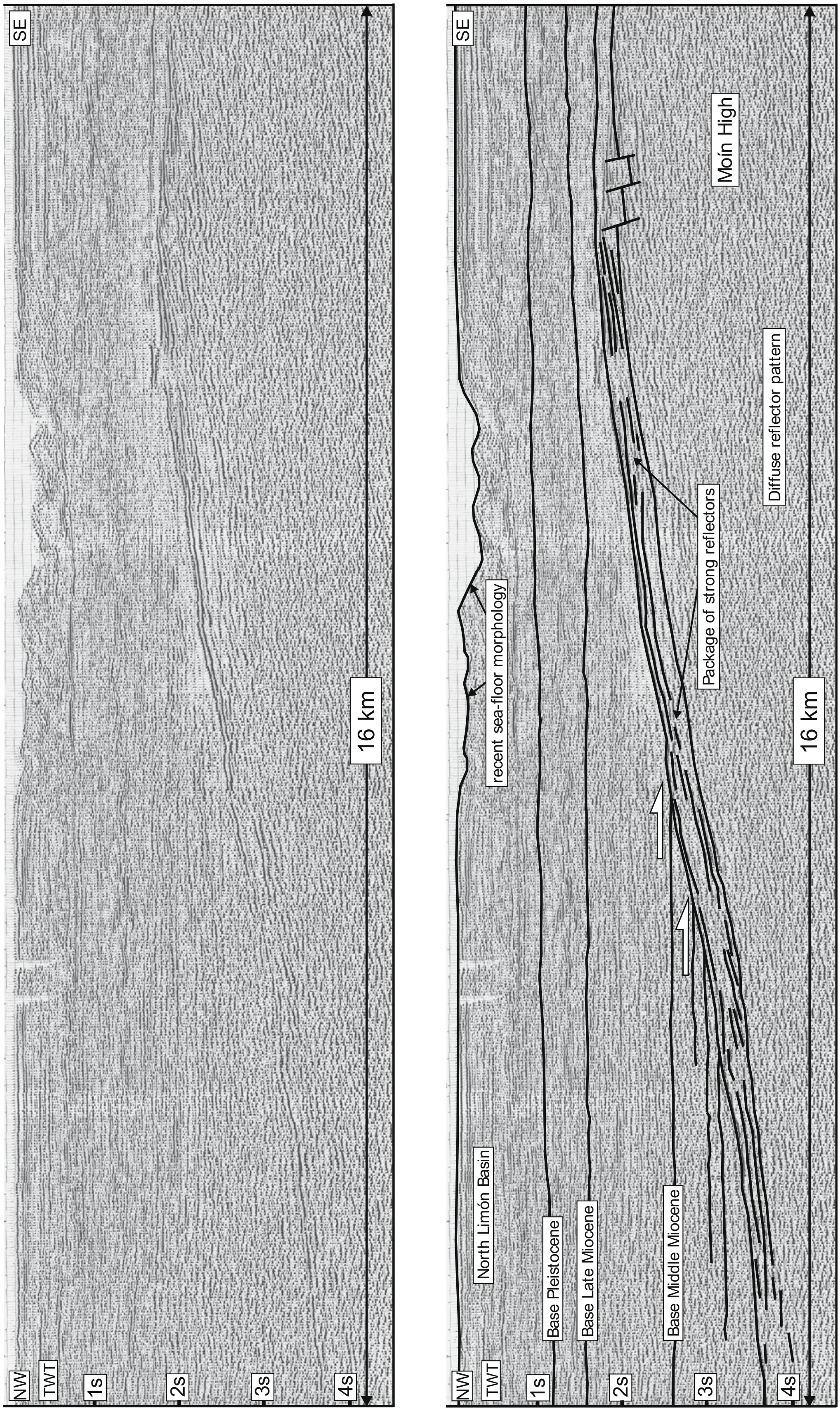

Fig. 5. NW–SE orientated section, parallel to the seismic line shown in Fig. 4, displaying the complete northwestern flank of the Moín High. A strong reflector package separates the Moín High from the surrounding and overlying sedimentary rocks of the North Limón Basin.

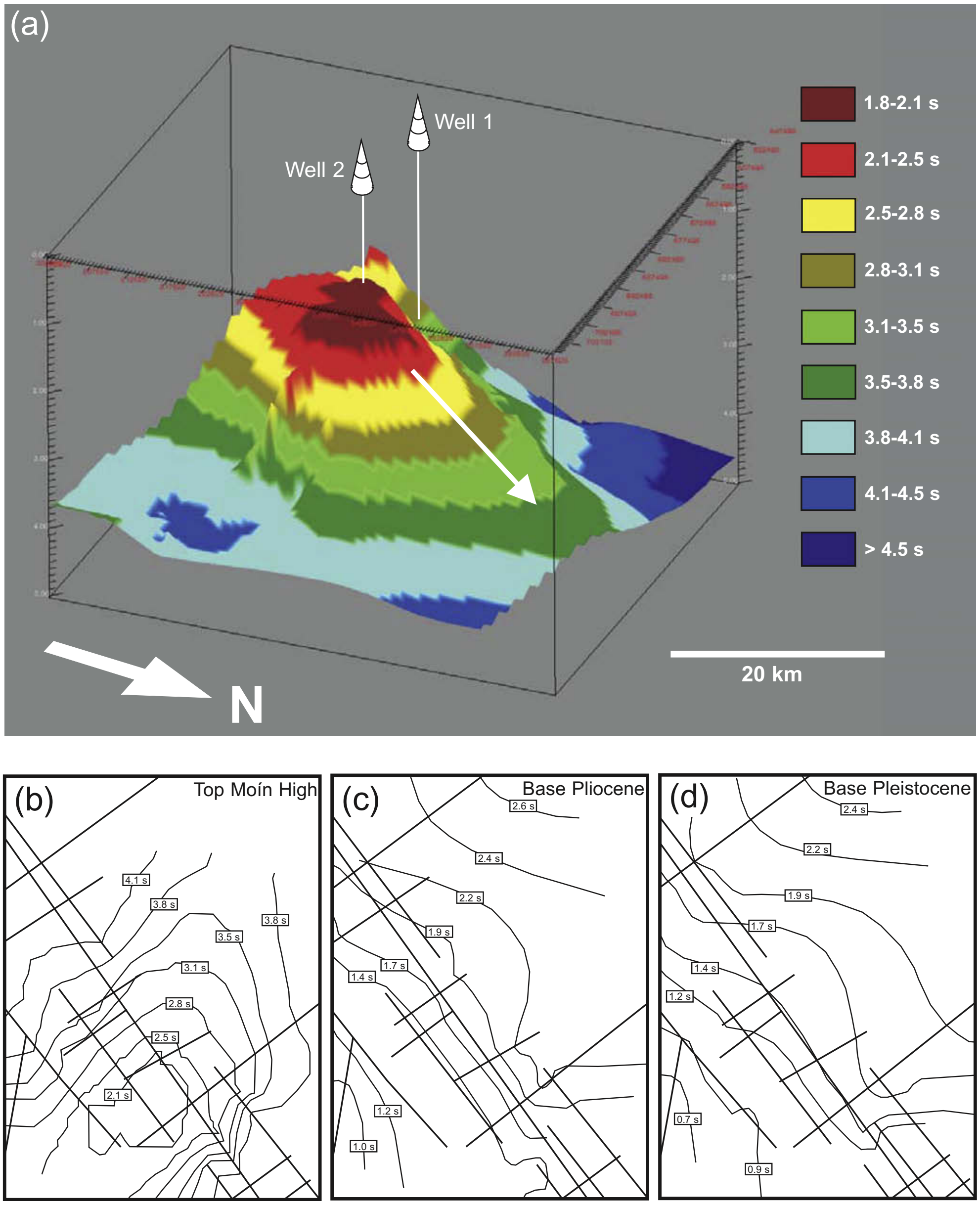

Fig. 6. (a) 3D Static model of the Moín High. The model shows that the structure has an elliptic outline and trends NNE–SSW. An axis can be reconstructed that plunges towards NNE. The northwest and southeast flanks are steep compared to the gently dipping northeast one. (b) Contour plot of the Moín High. (c) Contour plot of the Base Pliocene reflector. (d) Contour plot of the Base Pleistocene reflector.

curve at the location of Well 1 shows a linear subsidence trend interrupted by periods of up lift and non-deposition/erosion (Fig. 7).

Results derived from thermal basin simulations point towards a mean heat flow of 56–60 mW/m^2 (Brandes et al., 2008). From independent calculations based on Fourier's law a heat flow of 51 mW/m^2 was reconstructed. Vitrinites-depth plots derived from rocks of Well 1 indicate a maturity of 0.53 Ro% in a depth of 2820 m (Fig. 8a). In Well 2 a maturity of 0.45–0.50 Ro% was measured in a depth of 2080 m (Fig. 8b).

A long gap in the subsidence trend is visible. This gap is marked by the unconformity between the Middle Eocene and the Early Miocene. It is not clear whether the Upper Eocene and Oligocene sediments were eroded or whether they were never deposited in the Moín area. It is also difficult to estimate the amount of vertical uplift of the Moín High. To quantify the amount of erosion in a sedimentary basin, the method of Yamaji (1986) has been established. In this method, vitrinite reflectance data from a well will be plotted against the depth. The intersection of the abscissa and the ordinate is set at 0.2 Ro%. This value is characteristic for fresh vitrinites, which were not alternated. The abscissa with the vitrinite reflectance values has a logarithmic scale. Then the regression graph through all vitrinite reflectance values will be lengthened to 0.2 Ro%. The eroded sediment thickness can be read from the ordinate. For Well 1, 750 m of erosion is estimated with the Yamaji-method. For Well 2 the eroded thickness is 0 m. These results are problematic, as they would indicate the absence of erosion on the top of the Moín High but 750 m of erosion at the flank. The vitrinite data seems to be reliable, but such a trend can be disturbed by hot fluids or the presence of resedimented vitrinite derived from erosion of older rocks as has been described by Radke et al. (1997) and Taylor et al. (1998).

Based on the concentric shape of the Moín High, the onlap pattern and the wedging of reflector packages against the structure it

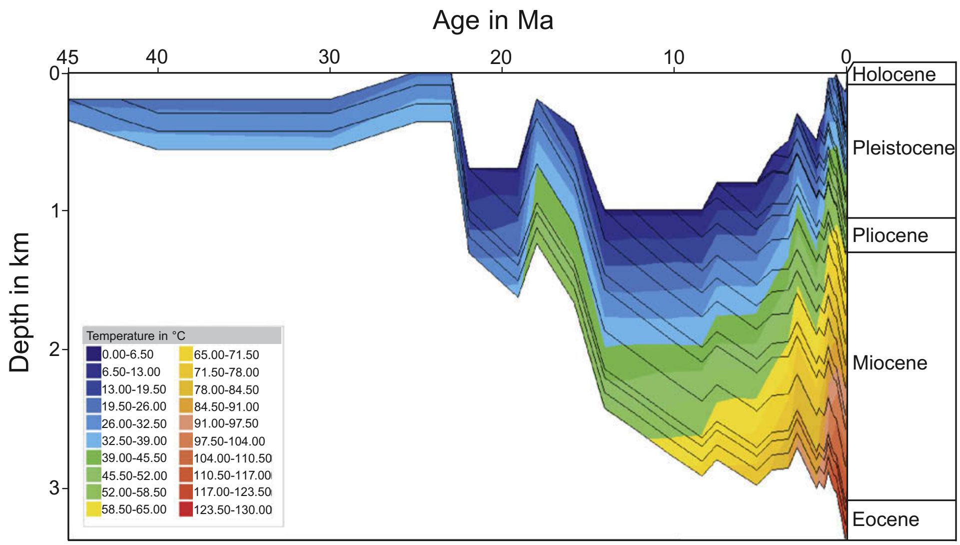

Fig. 7. Burial history at the location of Well 1. The subsidence trend is linear, interrupted by short phases of uplift during the late Early Miocene and the Middle Pliocene. The last three million years are characterized by a distinct increase in subsidence.

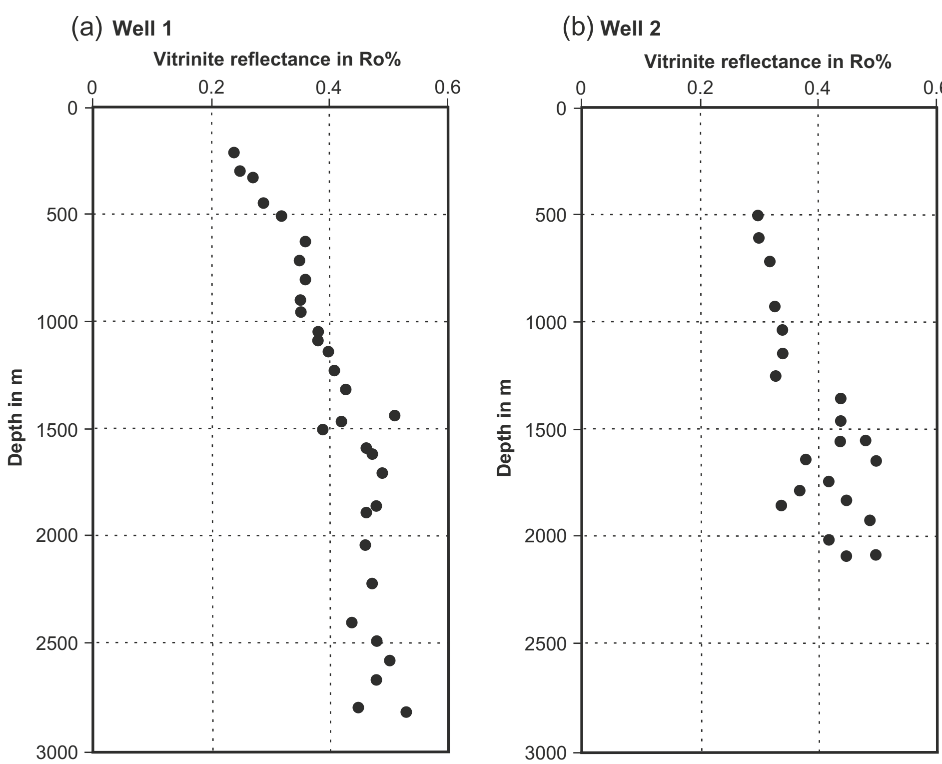

Fig. 8. (a) Vitrinite reflectance data of Well 1, indicating a normal maturity trend. (b) Vitrinite reflectance data derived from Well 2. Both graphs show a comparable maturity trend, whereas the data of Well 2 have a stronger scatter.

is likely that uplift and erosion was moderate. Much of the gap is probably caused by non-deposition. In the Middle Eocene the subsidence rate was low (Fig. 7). After the period of non-deposition, subsidence continued. This subsidence trend is interrupted by short phases of uplift during the late Early Miocene and the Middle Pliocene. The last three million years are characterized by a distinct increase in subsidence. This might be an effect of the extensional regime that established in the North Limón Basin at that time. Large listric normal faults support this idea (Brandes et al., 2007).

6. Discussion and interpretation

The most obvious explanation for the Moín High is the seamount origin. Seamounts are common features in an oceanic environment (e.g., Francis and Oppenheimer, 2004). They have a conical shape and consist of lava flows and volcaniclastic rocks (e.g., Orton, 1996). Bowland and Rosencrantz (1988) described isolated basement knolls 100–200 km offshore from the east coast of Costa Rica, which they interpreted as seamounts. Both Wells 1 and

2 terminate in Middle Eocene tuffs. Well 2 also penetrates two basaltic lava flows of Eocene age, which both have a thickness of approximately 10 m. The strong reflectors that envelope the Moín High indicate an increase in the acoustic impedance. This increase might result from the lithological change from sedimentary rocks to much denser basaltic rocks of the Moín High. In addition the strong reflector pattern on the northern flank of the structure may reflect an intercalation of lava flows and tuffs. The basaltic rocks in combination with the seismic data from the Moín High, fit very well to a volcanic seamount. Furthermore several seamounts like the Quepos Plateau are known from the west coast of southern Costa Rica (Lonsdale and Klitgord, 1978; Ranero and von Huene, 2000; Barckhausen et al., 2001). Though the seamount origin is very likely, there are also strong arguments against the seamount interpretation. The first one is the general absence of seamounts in East Costa Rica. The bathymetric maps from the Caribbean Sea show that there are no pronounced seamounts in the back-arc area (Smith and Sandwell, 1997). The seafloor of the adjacent Colombia Basin is also relatively smooth without a significant topography (Smith and Sandwell, 1997). Furthermore the volcanic activity that led to the formation of a seamount should have a pronounced thermal influence on the basin-fill. The paleo heat flow is reconstructed on the basis of vitrinite reflectance data. Vitrinites derived from Eocene sedimentary rocks of Well 1 indicate a normal maturity (Fig. 8a). The shape of the vitrinite profiles represents a normal sublinear trend. Thermal basin simulations point towards a constant mean heat flow of 56–60 mW/m^2 in the area of the Moín High (Brandes et al., 2008). There is no evidence for a higher heat flow or any thermal pulse during the evolution of the Moín High. Despite the occurrence of the basaltic rocks in the well, an origin as a volcanic seamount is very unlikely. In addition the tuffs and lava flows recorded in Wells 1 and 2 are consistent with observations of Mende (2001). Volcaniclastic rocks with intercalations of pyroclastic flows occur in different locations in the Limón Basin. Following Mende (2001) these rocks represent Eocene slope apron deposits, shed from the westward volcanic arc. Campos (2001) also described volcaniclastic breccias and conglomerates with intercalated basaltic lava flows from the Eocene Tuís formation. The outcrops are present along the front of the Talamanca Range in the area of Turrialba. Following these authors volcaniclastic rocks and basaltic flows were wide spread in the Limón back-arc area in Eocene times and do not necessarily reflect a seamount origin of the Moín High.

Another possibility to explain the origin of the Moín High is a laccolith that intruded into the fill of the Limón Basin in post Miocene times. The Talamanca Range in the west shows wide spread intrusive rocks (De Boer et al., 1995). Laccoliths are common in areas with magmatic activity and the convex shape of the Moín High would fit to an intrusion. If the structure is a laccolith is must be a young feature. At least post-Eocene. Such a young magmatic activity can be ruled out, because of the vitrinite profiles derived from Wells 1 and 2. There is no evidence for extensive thermal activity, which would be caused by the emplacement of a lakkolith. In a depth of 2820 m, Lower Miocene sedimentary rocks host vitrinites with a maturity of 0.53 Ro%. This maturity level coincides with the burial depth. The same is valid for Well 2. In a depth of 2084 m a maturity of 0.45 Ro% was measured (Fig. 8b). The present-day geothermal gradient in Well 1 is 3 °C/100 m (Astorga et al., 1991). The seismic data also provides arguments against a laccolith origin. A laccolith intrudes into a pre-existing sedimentary succession and as a consequence the sediments above the intrusion level will be warped up. As described above, the seismic data show a wedging of reflector packages against the structure. In addition clear onlaps are developed. These geometries are typical for a paleo-topography or a growing structure that was successively buried by younger sediments. Dengo (2007) identified fringing reefs on the flanks of the Moín High. This observation is also difficult to explain with a laccolith origin.

A salt pillow/diapir can be easily ruled out because of the lack of salt and shale in the Cretaceous and Lower Tertiary successions of the Limón Basin. The Cretaceous is represented by limestones (Mende, 2001; Campos, 2001) The Paleocene deposits are dominated by sandstones and conglomerates, which are interpreted as slope apron deposits (Mende, 2001). A diapir should also have rim synclines, which are not developed in the vicinity of the Moín High (Fig. 4a).

A package of strong reflectors envelopes the Moín High and separates it from the surrounding and overlying sedimentary rocks (Fig. 4a). The reflector package has a constant thickness and maintains it even on the crest of the structure. Therefore this unit can be interpreted as pre-growth strata. Well data show that Upper Eocene and Oligocene deposits lack on the northern flank of the Moín High. Middle Eocene deposits are directly overlain by Lower Miocene rocks. The wedging of reflector packages against the Moín High implies that the missing units might be present in the deeper parts of the basin. Because of their wedge-shaped geometry these units can be interpreted as growth strata (Fig. 4c). The lack of Upper Eocene and Oligocene deposits can be interpreted as a response to folding and uplift. From the growth strata geometry the evolution of the Moín High can be reconstructed (Fig. 9). Cretaceous to Lower Eocene deposits are pre-growth strata. During the Middle Eocene the first motions at the Moín High occured. Upper Eocene units show an onlap against the structure. In Oligocene times the vertical movements continued. Then deformation stopped and Lower Miocene deposits draped the structure. Slight vertical movements occurred during the Middle and Late Miocene. From the 3D static models it can be derived that the Moín High has an elliptic outline and a NNE plunging axis. This points towards a WNW–ESE directed compression.

Gursky (1986) described an Eocene deformation phase that created NE–SW trending folds on the Nicoya peninsula in West Costa Rica. A deformation phase of the same age is known from the Cabo Blanco Basin (Winsemann, 1992) and the Malpaís Basin (Schmidt and Seyfried, 1991). These basins are located on the North Costa Rica arc segment. South of the Trans Isthmic Fault System, the Eocene deformation phase can be observed in the Tarcóles Basin and the Parrita Basin (Campos, 2001). Reason for this deformation phase can be found in a convergence between North and South America that started in Eocene times (Gursky, 1986; Barrientos et al., 1997). Seyfried et al., 1991 pointed out that an increase in plate coupling between the Farallón and the Caribbean Plate might took place at that time and caused the observed deformation and uplift. Malfait and Dinkelmann (1972) gave a comprehensive overview of the tectonic evolution of the Caribbean region. They described a major reorganization of the tectonic plates in the Middle Eocene. The Caribbean Plate was decoupled from the East Pacific Plate (Malfait and Dinkelmann, 1972). Bowland (1993) showed that there was a strong sediment input into the Colombian Basin at that time. This underlines the impact of this deformation phase. Regarding age and geometry, it is likely that the Moín High evolved as a consequence of the Eocene deformation phase.

The seismic data show that the Lower Miocene unit also wedges out against the structure and that the Early Middle Miocene has a reduced thickness on top of the Moín High. Upper Miocene deposits still have a slightly reduced thickness on the crest. This pattern probably indicates the decline of the deformation. The Pliocene has a constant thickness in the North Limón Basin and on top of the Moín High and drapes the structure. Pliocene units above the crestal graben structure show an increased thickness, which might be related to ongoing subsidence of this graben. Quaternary deposits drape the whole area with a constant thickness. There is no evidence for vertical movements of the Moín High and large listric

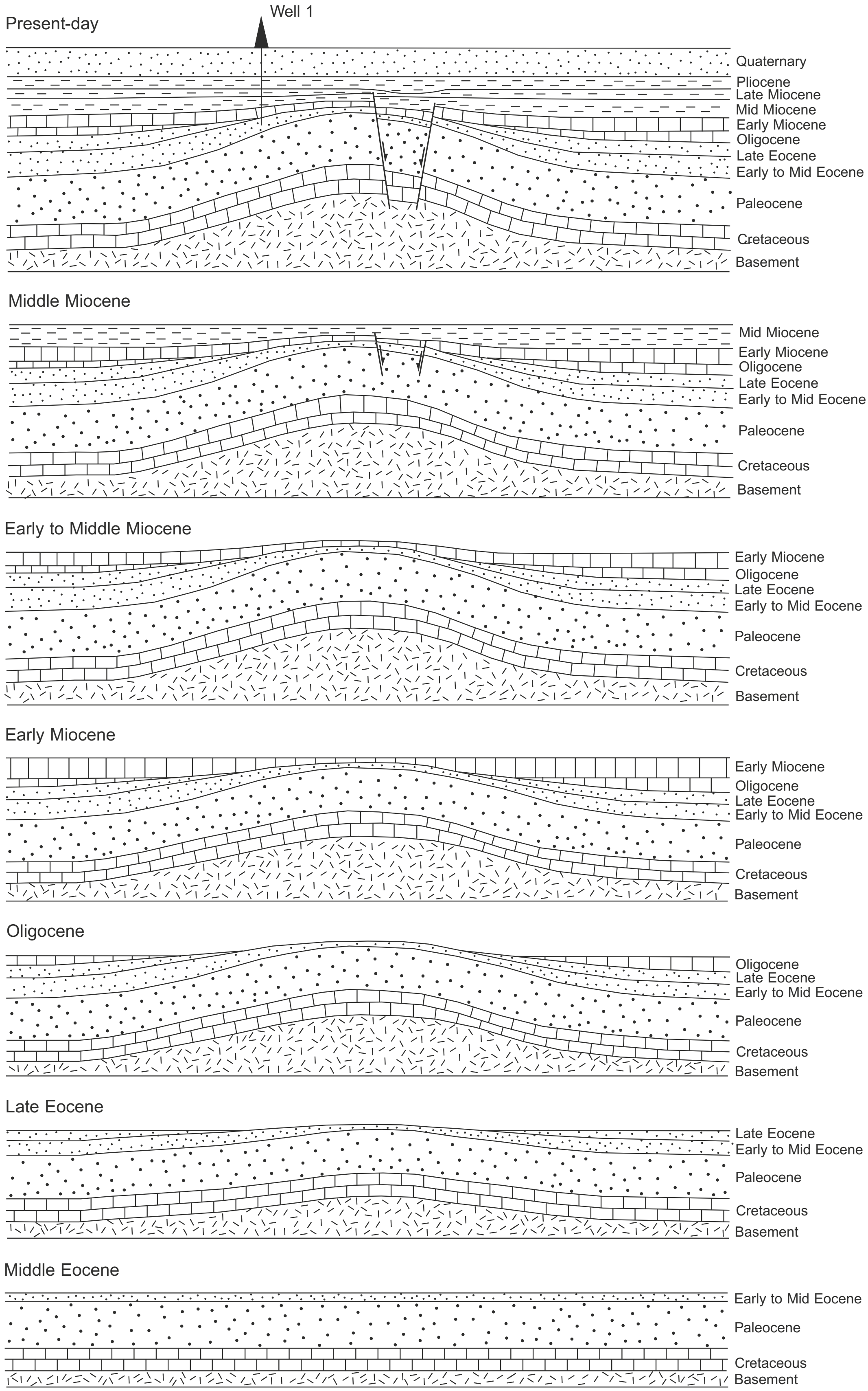

Fig. 9. The evolution of the Moín High derived from the growth strata geometry. Cretaceous to Lower Eocene deposits are pre-growth strata. They maintain a constant thickness even on the crest of the structure. During the Middle Eocene the first motions at the Moín High occured. Upper Eocene units show an onlap against the structure. In Oligocene times the vertical movements continued. Then deformation stopped and Lower Miocene deposits draped the structure. Slight vertical movements occurred during the Middle and Late Miocene. The crestal graben showed activity in Middle Miocene to Pliocene times.

NW–SE trending normal faults in the North Limón Basin give evidence for an extensional phase at that time (Brandes et al., 2007). Pliocene and Quaternary deposits are interpreted as post-growth strata. The seismic data imply that the Moín High is a contractional structure. Therefore the existence of an anticline is the most convincing explanation that takes all observations into account.

Regarding the compressional origin, the Moín High is possibly an inversion structure. Inversion is defined as a reactivation of normal faults as reverse faults. At least two deformation phases are necessary to create an inversion structure. First, an extensional phase with intense normal faulting has to affect the basin and later a compressional phase that reactivates the faults and transforms them into reverse faults. Inversion structures are well-known from sedimentary basins with a complex and multiple-phase history like the Central European basin system (e.g., Kockel, 2003; Mazur et al., 2005). Mende (2001) described a Paleocene extensional phase in the Limón Basin. With respect to the subsequent Eocene compressional deformation phase, inversion was possible, but there are no other true inversion structures described in Costa Rica so far. The seismic data also does not allow to verify this idea.

Several studies have shown that in southern Central America fore-arc and back-arc basins were affected by the low angle subduction of the Cocos Ridge (Protti and Schwartz, 1994; Kolarsky et al., 1995; Silver et al., 1995; Gräfe et al., 2002). Kolarsky et al. (1995) compared the Cocos Ridge with an indenter that hits the island-arc. Suárez et al. (1995) concluded that the Cocos Ridge does not subduct but collides with the trench. The present-day horizontal stress field in southern Costa Rica fits to an indenter scenario (Montero, 1994). Recent studies have shown that the subduction of the Cocos Ridge is very young. MacMillian et al. (2004) described an onset of subduction of the Cocos Ridge not before 2–3 Ma. Such an onset around 2 Ma, fits to the Plio-Pleistocene deformation phase observed in the external part of the Limón fold-and-thrust belt (Brandes et al., 2007). As shown above, the Moín High evolved in Eocene times. Because of the large time gap of c. 40 Myr, there is no relationship between the subduction of the Cocos Ridge and the evolution of the Moín High.

It can be also ruled out that the Moín High is related to the South Limón fold-and-thrust belt. The offshore part of the fold belt evolved in Plio-Pleistocene times (Brandes et al., 2007c). The onshore part is interpreted to have formed in the Miocene (Campos, 2001). A Miocene origin of the onshore part of the fold-and-thrust belt is supported by the timing of transforming the South Limón Basin from a back-arc basin to a retro-arc foreland basin (Brandes et al., 2008). The Moín High is clearly older than the South Limón deformed belt. In fact the Moín High acts as an obstacle for the propagation fold-and-thrust belt and causes the strong bend of the thrust in the northwestern corner (Brandes et al., 2007b,c).

The quality of the seismic data is not good enough to visualize the inner parts of the Moín High. Below the strong and continuous reflector pattern of the northern flank, the structure shows a more weakly layered pattern (Figs. 4a and 5). The central part shows a very diffuse reflector pattern that might reflect the limits of resolution. The diffuse pattern can be also interpreted as an indicator for basement rocks. Probably the Moín High is a basement-cored anticline, but there is no real evidence for this. The crustal structure of the southern Central American island-arc was described by Flueh and von Huene (2007). Velocity analyses indicate that the Central American land-bridge in the area of Costa Rica rests on oceanic basement of the Caribbean Plate (Sallarès et al., 1999). This means that the area of the Moín High is underlain by thickened oceanic crust of the Caribbean Large Igneous Province. If the Moín High is basement-cored, it would probably consist of basalt.

Regarding the closely related Trans Isthmic Fault System it is likely that the origin of the Moín High is somehow linked to this strike-slip fault. The Trans Isthmic Fault System is an E–W trending active strike-slip fault with major sinistral movements (Krawinkel and Seyfried, 1994; Krawinkel, 2003). Weinberg (1992) proposed that the Trans Isthmic Fault System is a former plate boundary and should be regarded as the southern boundary of the Chortis Block. Marshall and Fisher (2000) provided a comprehensive kinematic analysis of this fault system. They used the expression Central Costa Rica Deformed Belt for the east–west trending diffuse fault zone. Driving mechanisms for the evolution of the Central Costa Rica Deformed Belt are basal traction from the shallow subduction, shear and horizontal shortening due to the subduction of the Cocos Ridge and uplift caused by seamount subduction (Marshall and Fisher, 2000). Following Krawinkel and Seyfried (1994) the Trans Isthmic Fault System was active since the structuring of the earliest island-arc units. Large anticlines related to wrench tectonics are known from Panama (Wilcox et al., 1973). Marshall and Fisher (2000) observed transpression and crustal thickening in the back-arc area, related to the Trans Isthmic Fault System. This fits to the Moín High. There is no direct evidence on the seismic sections that the Moín High is, e.g., a positive flower structure, but the strong bend of the Trans Isthmic Fault System south of the Moín High might point to a transpressional origin in general (Fig. 3b). The Moín High is probably a transpression related anticline, which formed as a consequence of the movements along the fault zone. This interpretation also coincides with the geometry of the Moín High and the uplift history described above.

7. Conclusions

The Moín High is a large Eocene contractional structure located in the back-arc area of Central Costa Rica. The integration of seismic interpretation, well data, 3D static models and basin modelling techniques implies that the Moín High is an Eocene anticline structure. Support for an anticline origin is the vertical movements, which are recorded for the structure and the NNE–SSW trending axis, that fit to the Eocene deformation phase of the island-arc. In addition pre-growth, growth and post-growth strata can be clearly distinguished on the seismic sections. Probably the Moín High is a pressure ridge that is caused by transpression due to activity along the Trans Isthmic Fault System. A seamount origin can be ruled out because phases of uplift are unusual for a seamount. An origin as a magmatic intrusion is very unlikely because of the observed heat flow and vitrinite reflectance data. An evolution as a salt pillow/diapir can be ruled out because of the lack of salt in the back-arc area of southern Central America. The Moín High clearly is not related to younger events like the evolution of the Limón fold-and-thrust belt (Plio-Pleistocene) or to the subduction of the Cocos Ridge.

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