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Structure and Cenozoic evolution of Western Cuba fold and thrust belt

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Abstract: We present balanced and restored cross-sections across the Western Cuba fold and thrust belt, based on MCS profiles, field data and balancing techniques. The cross-section intersects the Los Palacios Basin, the Sierra del Rosario antiformal stack, the Bahía Honda unit, the frontal imbricated thrust sheets, the foredeep basin and a buried, geometrically inferred duplex. The minimum calculated shortening is 130 km. Syntectonic deposits and a forward kinematic model provide a good constraint for the Cenozoic tectonic evolution of the orogen, from the emplacement of the Bahía Honda unit to the final infill of the foredeep.

Keywords: Cuban fold and thrust belt, Caribbean plate, syntectonic sediments, balanced cross-section, kinematic modelling.

The structural models proposed for Western Cuba oppose transpressional (Pérez-Othon and Yarmoliuk, 1985; Millán, 2003) to thrust tectonics (Hatten, 1957; Pszczolkowski, 1994; Gordon *et al.*, 1997; Iturralde-Vinent, 1998; Moretti *et al.*, 2003). However, none of these models have been validated by means of balanced and restored cross-sections. We present the first balanced and restored cross-section of the Western Cuba fold and thrust belt using surface geology, borehole data and commercial reflection seismic data to decipher and illustrate the geometry and evolution of the area.

Geological and stratigraphic framework

The Cuban fold and thrust belt is part of the Greater Antilles Island Arc, which formed during the collision of the Great Caribbean Arc (Burke, 1988) with the North American continental margin from Late Cretaceous to Early Eocene (Gealey, 1980; Iturralde-Vinent, 1988). Subsequently, strike-slip faults fragmented the orogen (Rosencrantz, 1990), the deformation front migrated to the east, and the plate boundary jumped from the eastern margin of the Yucatan block to its current position along the Cayman trough (Stanek *et al.*, 2006). Currently, the Cuban fold and thrust belt is characterized by several outcrop areas separated by post-orogenic sediments (Fig. 1), with an arcuate shape resulting from a change in the structural grain from ESE-WNW in Central and Eastern Cuba to WSW-ENE in Western Cuba.

The Soroa cross-section intersects several structural units. The Los Palacios Basin, the southernmost unit of the cross-section, is a >3 km-thick basin filled with Upper Cretaceous to Pleistocene sediments (García-Sánchez, 1978), bound to the north by the kinemati-

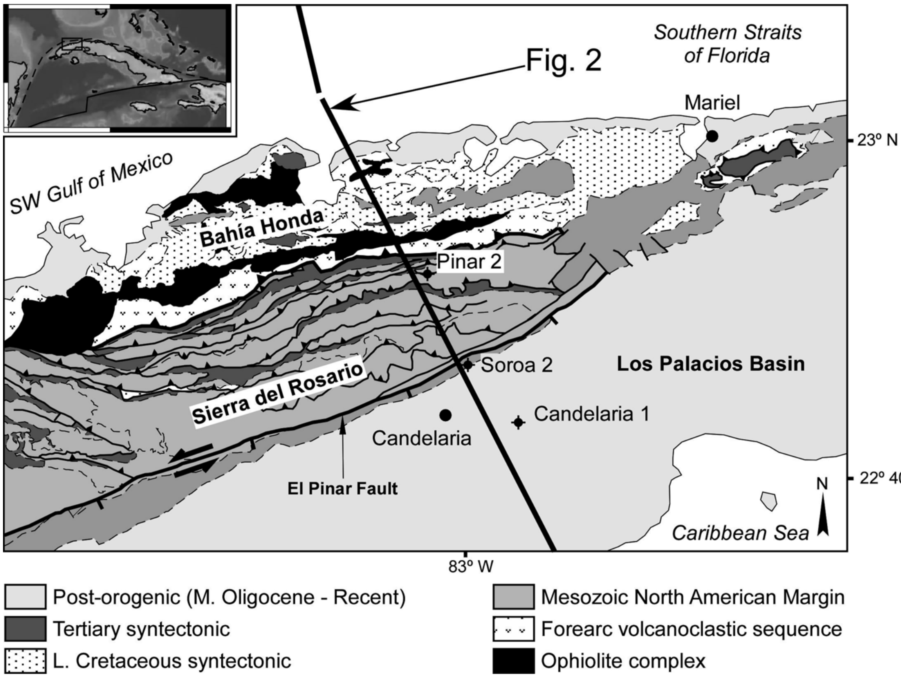

Figure 1. Geological sketch map of West Central Cuba (location in inset). The cross-section line and the location of the available boreholes are indicated.

cally complex El Pinar fault (Gordon *et al.*, 1997). North of this fault, the Sierra del Rosario unit contains rocks of the distal domains of the North American paleomargin (Iturralde-Vinent, 1998; Pszczolkowski, 1999; Saura *et al.*, 2008), displaying a deepening upward sequence, from continental synrift deposits to turbiditic and pelagic deep water sediments (Iturralde-Vinent, 1998; Moretti *et al.*, 2003). Paleocene to earliest Eocene syntectonic sediments can be seen across the whole unit. North of the Sierra del Rosario, the Bahía Honda unit is the westernmost extension of the Caribbean Arc. It contains a thick Cretaceous mélange of volcanoclastic deposits and serpentinites, uncomformably overlain by Tertiary flysch sediments. The northern part of the transect, located offshore, is well imaged by commercial reflection seismic data. Three stratigraphic members of unknown lithostratigraphy were differentiated: Jurassic to Middle Cretaceous North American margin deposits (Moretti *et al.*, 2003), Upper Maastrichtian to Lower Eocene syntectonic sequence and Middle Eocene to Recent pelagic chalks.

Structure through the Soroa cross-section

In the southern boundary of the section, the Los Palacios Basin is formed by a layer-parallel, subhorizontal succession in the south and a northern domain, where subhorizontal horizons overlie progressively steeper layers, defining a north-converging, fanned attitude. The resulting pinch out allows the outcrop of Late Cretaceous rocks. The Sierra del Rosario tectonic unit defines a wide antiform cored by Mesozoic and Paleocene rocks, with a gently S-dipping southern limb and a moderately N-dipping northern limb, which becomes steeper to overturned northwards. The antiform is built up by several ENE-WSW-trending, >1 km-thick thrust sheets containing only the Mesozoic cover and the Paleocene olistotrome, which suggest a thin skinned tectonic style. The kinematic indicators measured through this domain show a mean NNW direction of tectonic displacement, which together with the above described geometric and stratigraphic characteristics, allows us to define the Sierra del Rosario unit as an antiformal stack. The Bahía Honda unit is a 3 km-thick tectonic unit characterised by an intensely thrusted and folded volcanoclastic Cretaceous sequence, overlain by gently deformed Tertiary sediments, and thus postdating most of the internal deformation of the Bahía Honda thrust sheet. There is no record of interlayered Sierra del Rosario and Bahía Honda domains in the available maps and borehole data, which indicates that these are two decoupled units, as is also suggested by the basal thrust of the Bahía Honda unit mostly overlying the Paleocene olistostrome. We therefore interpret the Bahía Honda unit as being the allochthonous accreted forearc, resting on top of the Paleocene olistostrome, currently depicting a large asymmetric synform (Saura *et al.*, 2008).

The proposed structure of the Soroa cross-section offshore based on the interpretation of 3D seismic survey shows three domains. 1) A system of parallel reflections in the northern part, which is interpreted to be the Mesozoic Florida-Bahamas margin (e.g. Moretti *et al.*, 2003), 2) a poorly imaged sector in the south, roofed by a N-dipping reflection, which we interpret as the offshore segment of the Cuban fold and thrust belt, and 3) a zone of parallel, continuous reflections that can be traced along the whole seismic profile, imaging the sedimentary infill of the Cenozoic foreland basin.

At the base of the fold and thrust belt, a set of reflections can be consistently traced across the whole area, which according to their reflection character can be correlated with the pre-Kimmeridgian sequence of the Florida margin. On top of these reflections, a semi-transparent section occurs, whose northern boundary coincides with a vertical offset of the pre-Kimmeridgian sequences. We interpret this geometry as indicating a Late Jurassic-Early Cretaceous normal fault. South of this area, a system of imbricated thrust sheets duplicating the North American margin can be recognized.

The reflections of the foreland basin are onlapping northwards onto the Florida margin. Southwards, the deepest reflections are truncated by a thrust of the fold belt, although upsection, they are also onlapping onto the taper of the belt. The lower horizons of the Cenozoic infill depict an antiform at the deformation front, whose northern limb is characterised by an upsection decrease of the dip of the reflections, typical of growth strata. These sediments, which are known to be pre-Middle Eocene, record the main deformation stage. The thrust system detaches along the Kimmeridgian layers, as suggested by the seismic data, incorporating up to the lowermost layers of the Cenozoic sequence. The Lower Eocene to Oligocene sediments uncomformably lying on top of these units mainly postdate their emplacement, although minor, late reactivations can be identified.

Balanced and restored cross-sections

Balancing techniques have been used to construct a best fit balanced cross-section, overcoming the lack of data at depth. The assumptions made are: 1) a thin-skinned deformation style only involving cover rocks, 2) these rocks are detached close to the top of the Kimmeridgian, and 3) the Paleocene olistostrome is an effective detachment level, enhancing structural decoupling. The restored cross-section was constructed by extending the distal Florida platform. The resulting length is constrained by the six thrust sheets needed to infill the area between the proposed base of the Bahía Honda thrust and the inferred regional detachment. This system implies certain uplift of the Bahía Honda unit but does not account for the current configuration of the Sierra del Rosario antiformal stack. We therefore include deeper rocks to generate an antiform that deforms the already emplaced units.

The restored cross-section to the K/T boundary shows lateral continuity between the Florida platform in the north and the Sierra del Rosario in the south, and requires the Bahía Honda thrust sheet to be restored to a southernmost position than the Sierra del Rosario units. The minimum displacement to the NNW of the trailing pin line of the North American margin is 85 km, and the minimum for the southernmost part of the Bahía Honda thrust sheet is 130 km (Fig. 2).

Discussion: kinematic evolution of the Western Cuba fold and thrust belt

Using the large-scale cross-cutting relationships we interpret that the Bahía Honda unit was emplaced first on top of platform sediments, which were subsequently involved in the deformation that formed the main tectonic edifice of Western Cuba. Finally, the basement was involved, creating a large antiform at the back of the thrust system. Subsequent uplift and concomitant erosion allowed the current outcrop of the Sierra del Rosario unit and the isolation of the Bahía Honda thrust sheet. The Los Palacios Basin formed slightly later than the basement antiformal stack.

The restored cross-section has been used as a template to perform a forward kinematic model, using the Fault Parallel Flow algorithm from mve's software 2DMove® (Fig. 3). Since we interpret most of the strike-slip deformation as being recorded by the El Pinar fault and the effects of this stage as being of minor importance north of it, 2D modelling is an acceptable approach. The kinematic model is constrained by cross-cutting relationships between thrusts and well-dated syntectonic deposits. The initial configuration (65.5 Ma) shows the K/T sediments uncomformably overlying the non-deformed Sierra del Rosario and the already deformed Bahía Honda units. In the first model step (Fig. 3b), from Danian to Selandian (65.5 to 60 Ma), the Bahía Honda unit overthrusted the North American margin, on top of which olis-

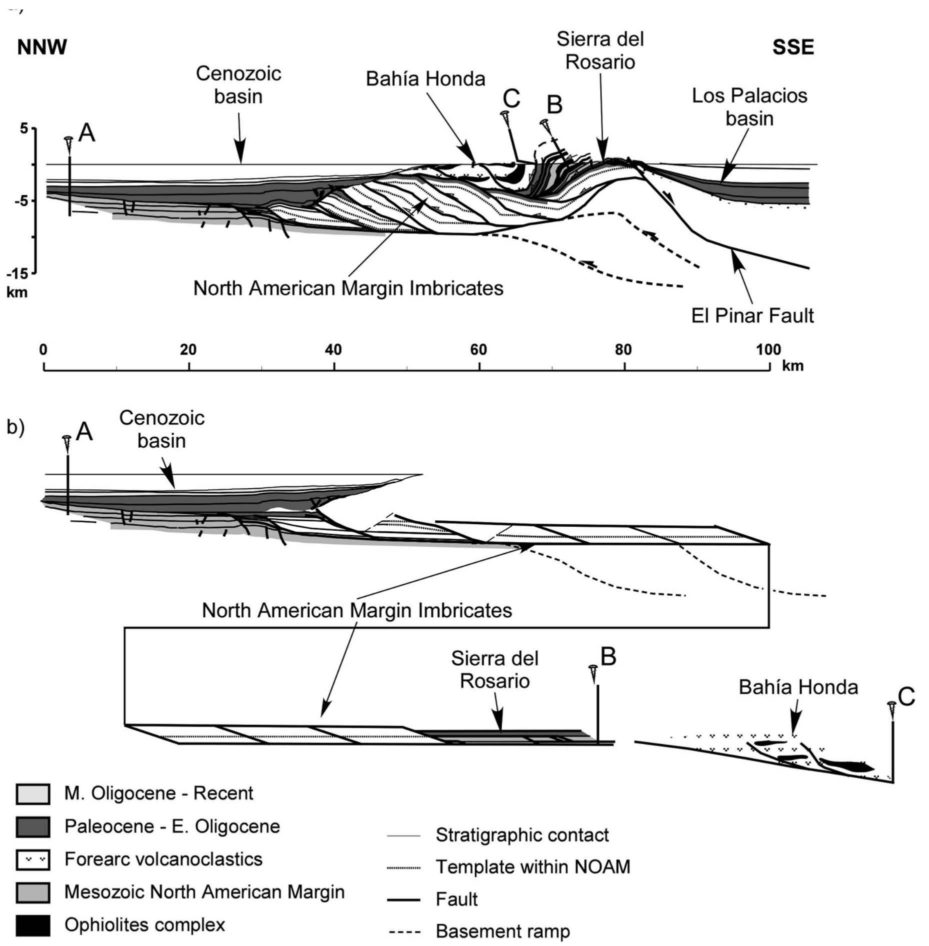

Figure 2. Best fit balanced (a) and restored (b) cross-sections constructed by combining onshore and offshore data and using balancing techniques.

tostromic sediments were shedded, with the associated dismantlement of the volcano-clastic unit. Coevally, sedimentation also occurred on top of the Bahía Honda unit. In the following two model steps (Figs. 3c and 3d), from Selandian to Thanetian (60 to 56 Ma), the North American margin cover duplexed underneath the Bahía Honda unit, which resulted in the formation of the Sierra del Rosario antiformal stack and the currently buried cover thrust sheets. Sedimentation in front of the advancing prism and in the piggy back basins kept occurring. The fourth step (Fig. 3e), from Thanetian to Lutetian times (56 to 45 Ma), corresponds to the final emplacement of the basement slices. This stage produced significant uplift, tilting and concomitant erosion. During the same period, relatively thick Lower Eocene deposition in the foredeep basin largely concealed the accretionary prism, recording the final activity of the foremost thrusts. The infill of the Los Palacios basin also started during this period. The fifth step (Lutetian-Recent; <45 Ma) corresponds to a major change across the entire northern Caribbean region, when major sinistral strike slip faulting occurred (Fig. 3f). The final geometry of the presented evolutionary model fits reasonably well with the balanced geological section (Fig. 3g).

Conclusions

The balanced Soroa cross-section and a forward kinematic model illustrate the current geometry and Cenozoic evolution of the Cuba fold and thrust belt. The Bahía Honda accreted forearc emplaced from Danian-Selandian (65.5 to 60 Ma) on top of the North American margin, whose successive accretion resulted in the formation of the Sierra del Rosario antiformal stack and frontal imbricate system (Selandian to Thanetian). The latter emplacement of a deep duplex completed the 130 km of shortening. Associated uplift and concomitant erosion isolated the Bahía Honda unit while allowing the Sierra del Rosario units to crop out. In front of the system, the 4 km-thick foredeep basin filled during and after the end of deformation and, onshore, the final transtensional stage was recorded by the Los Palacios Basin.

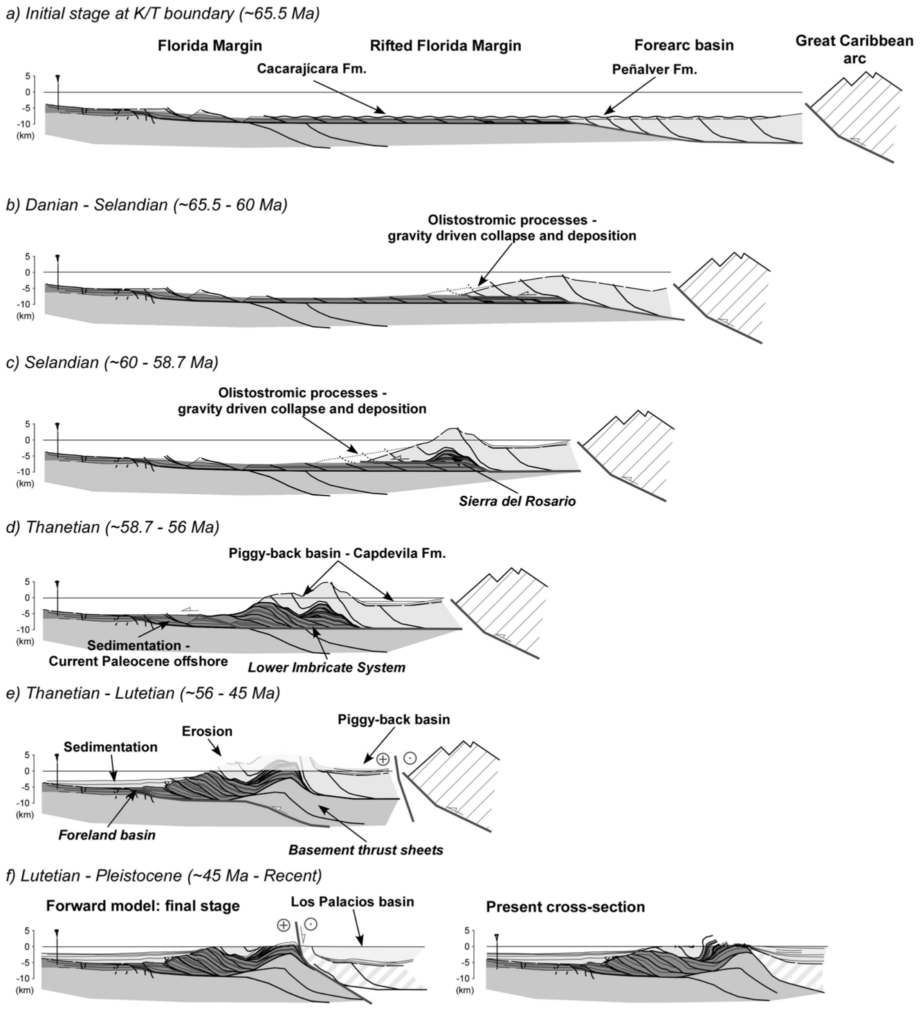

Figure 3. Successive stages of a kinematic forward model performed along the transect. (a-e) Compressive phase (Paleocene-Early Eocene), (f) final transtensional stage (Middle Eocene-Recent). The final result is compared with the balanced cross-section. The paleodepths are inferred from the facies of the syntectonic sediments.

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