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# Analysis of Curved Folds and Fault/Fold Terminations in the Southern Upper Magdalena Valley of Colombia Giovanny Jiménez Díaz<sup>1</sup>, Jhon Rico<sup>1</sup>, German Bayona<sup>1, 2</sup>, Camilo Montes<sup>1, 2</sup>, Alexis Rosero<sup>3</sup>, Daniel Sierra<sup>3</sup>

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#### Abstract

We use surface and subsurface fold and fault geometries to document curved geometry of folds, along-strike termination of faults/folds and the change of dip of regional faults in four structural areas in the southern part of the Upper Magdalena Valley Basin. In La Cañada area, strike-slip deformation is dominant and cuts former compressional structures; faults and folds of this area end northward abruptly near Rio Paez. To the north of Paez River is the La Hocha area that includes the Tesalia Syncline and La Hocha Anticline, two curved folds that plunge at the same latitude. The southern domain of La Hocha Anticline is asymmetric and bounded by faults in both flanks, whereas the symmetry of the northern domain is related to subsurface fault bending. Paleomagnetic components uncovered in Jurassic rocks suggest a clockwise rotation of  $15.2 \pm 11.4$  in the southern domain, and  $31.7 \pm 14.4$  in the northern domain. The Iquira Area, North of La Hocha, the internal structure is controlled by east-verging faults that end abruptly to the north of this area. The northernmost area is the Upar area that includes fault systems with opposite vergence; west-verging faults at the east of this area decapitate east-verging faults and folds.

Paleomagnetic data, geologic mapping and regional structural cross sections suggest that: (1) pre-existing basement structure controls the curved geometry of La Hocha Anticline; (2) along-strike changes in structural style between adjacent areas and along-strike termination of faults and folds are related to the location of northwest-striking transverse structures in the subsurface; and (3) at least two deformation phases are documented: an Eocene-Oligocene phase associated with the growth of folds along detachment levels within Mesozoic rocks; and a late Miocene phase associated with transpressive faulting along the Chusma and San Jacinto faults. The latter event drove clockwise rotation of the La Hocha Anticline.

Keywords: Curved folds; La Hocha Anticline; Deformation; Transpression; San Jacinto Fault.

#### **1.0 Introduction**

The origin of curved orogenic belts has been associated either with orocline deformation or the resultant geometry of pre-existing structures (Weil and Sussman, 2004). The term "orocline", defined by Carey (1955), has been linked to a straight mountain that has been flexed or curved to its current shape by a continuous deformation phase of progressive rotational thrust displacements. Another possibility to create a curved fold can be related to the anisotropy of the basement; in this case, the paleo-basin geometry controls the geometry of curved folds. Other definitions have been used to describe any orogen of arcuated shape, regardless of its deformational history (Eldredge et al., 1985). This paper considers whether curved folds and along-strike termination of faults are associated with transverse zones. A transverse zone has been identified and described in other trust belts systems, for example, the Appalachian thrust belt (Thomas, 1990; Thomas and Bayona, 2002).

Transverse zones can be defined as the abrupt termination of faults, plunge folds and changes in verging faults. This anisotropy in depth control the deformation in upper levels of the sedimentary beds during the shortening, causing change in the structural style between adjacent areas (Fig. 1). The oblique alignment of terminations, as well as plunging and verging changes with respect to the strike of the mayor structures in map view in general, are grouped in a transverse zone. In some cases these transverse zones are associated with transference zones in rift basins, such as The Suez and the Red Sea rifts (Moustafa, 2002).

These transverse structures may be confused with strike-slip faults, but they are tear faults bounding segments of thrust sheets (Figure 1). Many of these cross-strike features may be underlain by lateral ramps that serve to transfer decollements from one stratigraphic level to another in the same manner as the frontal ramps, but in a direction normal to the strike of the fold belt (Pohn, 2000).

During the Triassic to Early Cretaceous the Upper Magdalena Valley Basin was affected by rifting (Sarmiento, 2001). Those older structures related to rifting in the Upper Magdalena Valley Basin can be the control of thickness variations; during the shortening or transpression phases control the structural style and limited structural areas.

In the Southern Upper Magdalena Valley Basin of Colombia (Fig. 2), mapped faults and folds have gentle (15–20 degree) curvatures, and abruptly end along strike and regional faults showing along-strike variations of dip angle. The aim of this paper is to determine whether there is a genetic relationship in the evolution of these structures. We carried out field geological mapping in a total area of 1,200 km<sup>2</sup>, performed structural analysis and conducted paleomagnetic work. Two hypotheses are considered to explain the evolution of curved folds: (1) the vertical-axis block rotation of originally straight fold axis; or (2) the original geometry of the basin has bends that affected the distribution of strata and deformation. To test which of these two hypotheses may explain the curved shape, we focused our analysis on a curved anticline, La Hocha Anticline, because volcanic and sedimentary rocks of Jurassic, Cretaceous and Cenozoic age could record paleomagnetic directions useful for this type of analysis.

### 2.0 Geological and tectonic setting of the study area.

The Magdalena Valley Basin is divided by the oil industry into three segments, from south to north: Upper, Middle and Lower basins. The Upper Magdalena Valley Basin (UMVB) is related genetically to the growth of the bounding Central and Eastern Cordilleras (Butler and Schamel, 1988). The Natagaima–La Plata basement-cored high divides the Upper Magdalena Valley Basin into two basins: the Girardot and Neiva basins (Butler and Schamel, 1988). The Neiva Basin), is bordered to the west by the east-verging reverse Chusma Fault and to the east by the west-verging Garzon Fault, includes volcaniclastic rocks of Triassic and Jurassic age, marine sedimentary rocks of the Cretaceous period, and continental sedimentary rocks of the Cenozoic era (Butler and Schamel, 1988).

In the study area, where the traces of fold axes and faults have a curved geometry (Velandia and Nuñez, 2001), is restricted to the western zone of the Neiva Basin (Fig. 2). The following are the major structures affecting the study area, from west to east: La Plata-Chusma Fault system, which places Jurassic plutonic and volcaniclastic rocks next to Cenozoic strata; the Tesalia Syncline and La Hocha Anticline, between La Plata-Chusma Fault system and the reverse east-verging San Jacinto fault (De Freitas, 2000); and to the east, the study area is limited by Matambo, San Jacinto and Upar faults (Fig. 3).

The lowermost unit of the Jurassic to Cenozoic stratigraphic sequence in the Neiva Basin is the Jurassic Saldaña Formation, which is composed of volcaniclastic rocks (Fig. 4). Outcrops

of the Saldaña Formation are located in the core of La Hocha Anticline, and at the hanging walls of the Chusma and Upar faults. Cretaceous rocks in the Neiva Basin include the Caballos, Villeta, and Monserrate formations, which accumulated in marine environments (Guerrero et al., 2000). These units crop out, from north to south, in the footwall of the westverging Upar Fault, in both flanks of the La Hocha Anticline, and to the south of the Paez River in the hanging wall of San Jacinto Fault, as well as in the hanging wall of west-verging La Cañada and Matambo faults (Fig. 3). The Caballos Formation rests unconformably upon the Saldaña Formation and is composed of sandstones and red mudstones. The Villeta Formation rests in a transitional contact over the Caballos Formation, and is composed of black shales, mudstones and limestones. The Monserrate Formation overlies the Villeta Formation, and it is composed of fine-grained quartzose sandstones. The Maastrichtian-Paleocene Guaduala Formation rests over the Monserrate Formation in a paraconformity (Veloza et al., 2006). Continental deposition begins with the Guaduala Formation that consists of red and gray mudstones, and coarse-to-medium-grained, lithic-bearing sandstones. Conglomerate beds of the Palermo Formation disconformably overlie the Guaduas Formation. The Bache Formation overlies the Palermo Formation, and it is composed of mudstones, sandstones, and conglomerates. The Tesalia Formation is a conglomeratic unit that generates the highest slopes within the Cenozoic succession. This unit unconformably overlies the Bache Formation, and underlies fine-grained lithologies of the Potrerillos Formation. The Doima Formation, the third conglomeratic unit in the Neiva Basin, disconformably overlies the Potrerillo Formation and underlies volcanic green sandstones of the Miocene Honda Formation.

Previous works in the Upper Magdalena Valley Basin propose different deformations phases, with compressive and strike-slip movements (Benavente and Burrus, 1988; Fabre, 1995, Ramon & Rosero, 2006). Those works focused on the regional evolution of the Upper Magdalena Valley Basin, but do not explain the evolution of local curved folds or along-strike termination of faults.

## 3.0 Methods

We carried out a geological mapping at a scale of 1:25,000 in the study area shown in Figure 3. Structural cross-sections were made using the collected field data, subsurface data (2-D

seismic reflection profiles and wells supplied by HOCOL S.A.), and regional geologic maps (Marquínez et al, 2002).

Twenty-nine sites were sampled for paleomagnetic analysis using a portable core drill. The paleomagnetic samples were obtained from the Saldaña, Caballos, Villeta, Guaduala, Bache, and Potrerillos formations. Alternate fields (AF) and thermal progressive demagnetization analyses were carried out at the paleomagnetic laboratories of the Universidad de Buenos Aires University (AF and thermal), and Sao Paulo University (AF). Components of magnetization were calculated by means of Principal Component Analysis (Kirschvink, 1980) interpreted with the aid of orthogonal demagnetization diagrams (Zijderveld, 1967). Mean magnetization directions were calculated using Fisher's statistics (Fisher, 1953). Components with k values less than 10 are indicated as directions with high dispersion, and sites with k values less than 15 were not used for calculation of mean directions (Table 1).

We used two steps of tilt correction for the determination of characteristic directions of the Saldaña Formation (Jurassic age). Bedding (DD/D=dip direction/dip angle) indicates the attitude of the Saldaña Formation beds at the present stage of deformation. Correction 1 calculates mean-site directions and Cretaceous bedding for Jurassic beds (KrDD/KrD), using the attitude of overlying Cretaceous beds. Correction 2 calculates mean-site directions assuming that Jurassic beds are accumulated on a horizontal surface.

Local incremental tilt tests (McFadden and Reid, 1982) were used to determine the timing of magnetization with respect to Cretaceous deformation. The significance of the tilt test followed the criteria of McElhinny (1964), owing to the limited number of sites per structural domain. For vertical-axis rotations, the confidence limits for structural domain declinations, and the relative difference of declinations with an arbitrary point in the stable craton, follow the criteria given by Demarest (1983).

## **4.1 Structural analysis**

Plunging folds, change in structural style and detachment levels, and alignment of structures allowed us to define 4 areas in the region (Fig. 3), from south to north: 1) La Cañada area; 2) La Hocha area; 3) Iquira area; and 4) Upar area. In the next section, we describe the geometry of regional and local structures on the basis of map patterns and structural cross-sections.

## 4.1.1 La Cañada Area

High-angle, opposite vergence faults, characterize the structure to the south of the Paez River. The north-striking Matambo Fault ends to the north of the Paez River, as a northeast-striking fault. La Cañada Fault ends abruptly to the north, as well as its related asymmetrical northwest-verging fold (Fig. 3A). The trace of the San Jacinto Fault across the Paez River is uncertain; to the south, the San Jacinto Fault places Lower Cretaceous units against different units of Cenozoic age.

In cross-section, the east-verging San Jacinto Fault, and the west-verging La Cañada and Matambo faults involve rocks of the Saldaña Formation (Fig. 5A and 5B). The high-angle dipping, northwest-verging Cañada and Matambo faults bound a low-dipping structural domain, whereas to the west and east, Cretaceous and Cenozoic strata dip steeply. Further to the west, the San Jacinto Fault affects the western domain of this low-dipping structural domain. Further to the east, strata of the Honda Formation are folded and follow the geometry of older Cenozoic strata deformed by the Matambo Fault system (Fig. 5A and 5B).

# 4.1.2 La Hocha Area

The main structures are, from west to east, the Tesalia Syncline, La Hocha Anticline and the San Jacinto Fault (Fig. 3A). La Hocha Anticline is divided into northern and southern domains, according to the trace of the fold axis. Below is a description of each domain and its relationship with the San Jacinto Fault.

**Southern Domain.** The La Hocha Anticline in the southern domain is asymmetric, the fold axis has a northeast trend, plunges to the north and south, and it is bounded by faults in both flanks (Fig. 3A). The eastern flank is affected by two east-verging fault systems: the low-angle La Hocha Fault and the high-angle San Jacinto Fault. Both faults involve rocks of the

Jurassic Saldaña Formation (Fig. 6 and Fig. 6B). ). The west-verging Mesitas Fault bounds the western flank of the anticline (Fig. 6 and Fig. 6B), The trace of the axis of the anticline is parallel to the trace of the low-angle La Hocha Fault. In contrast, the level of detachment in the hanging wall of the San Jacinto Fault changes southward from Jurassic to Cretaceous units to the south, whereas in the footwall the presence of vertical and overturned Cenozoic beds striking parallel to the fault is consistent. To the north of the Paez River, the geometry of footwall Cenozoic strata changes from vertical beds to local-scale folds with low dip angle; these folds are covered by quaternary deposits (Fig. 3). The back limb limb of La Hocha Anticline is deformed by east-west strike-slip faults cutting the Villeta, Monserrate and Guaduala formations. These faults were also observed in the northern domain.

**Northern Domain.** La Hocha Anticline in the northern domain is symmetric, its fold axis has a north-northwest trend, and plunges to the north and south (Fig. 3A). The eastern flank is affected by three east-verging fault systems, involving rocks of the Jurassic Saldaña Formation (Fig. 7). The low-angle La Hocha Fault runs parallel to the trend of the fold axis, and only affects rocks of the Saldaña Formation. The high-angle San Jacinto Fault has a similar strike and subsurface geometry as the one described for the southern domain (Fig. 7). The San Jacinto Fault places Cretaceous rocks against high-angle dipping to overturned Cenozoic rocks that include strata of the Honda Formation. In the middle of these two faults is the high-angle Buenavista Fault that places Saldaña Formation in contact with Cretaceous rocks. The latter rocks form two synclines whose fold axes have different trends (Fig. 3). In the western flank, Cretaceous units are folded by blind faults, which are interpreted as splays of the La Hocha Fault (Fig. 7). In the northern domain, the strike of Cretaceous beds is parallel to the trend of the axis of the Tesalia Syncline, and to the strike of Cenozoic beds in the eastern flank of the Tesalia Syncline.

At similar latitude of the northern plunge of the La Hocha Anticline, the traces of La Hocha, Buenavista and San Jacinto end abruptly, and a new north-striking fault detaching in Upper Cretaceous rocks appears. This fault is an eastern splay of the north-striking Teruel Fault (see Iquira Area) that ends abruptly to the north of the northern plunge of the La Hocha Anticline. Following to the west, the trend of the Tesalia Syncline and the strike of the east-verging Pacarni Fault system change from north-south to northeast. In this sector, the Tesalia Syncline plunges southwestward.

#### 4.1.3 Iquira Area

West-dipping Cenozoic and Cretaceous strata affected by east-verging faults characterize this structural area. The east-verging Chusma Fault system, that places Jurassic intrusive rocks against Cenozoic rocks (Fig. 3B), marks the western boundary of this area. East-verging Pacarni and Teruel faults have detachment levels in Guaduala and Upper Cretaceous rocks, respectively (Fig. 8). In contrast, the high-angle Buenavista Fault detaches in the Saldaña Formation and tilts the hanging-wall of the Teruel Fault. To the north of this area, the Chusma Fault system cuts the Pacarni Fault system, and the strike of the Chusma Fault changes from northeast to north-northeast. Additionally, Cretaceous rocks of the Monserrate Formation in the hanging wall of the Teruel Fault and the trace of the fault end abruptly, while strata of the Guaduala Formation are involved in local folds.

#### 4.1.4 Upar Area

Opposite vergence fault systems are the main structural characteristic of this area (Fig. 3). The high-angle and east-verging Chusma Fault, with detachment in Jurassic intrusive units, bounds this area to the west. To the east, the low-angle and east-verging San Francisco Fault system detaches within the upper Guaduala Formation, whilst the low-angle and east-verging Palermo Fault system detaches within the Cretaceous Villeta Formation (Figs. 3 and 9). In the surface, several folds involving Cretaceous and Cenozoic strata are associated with these fault systems. To the east, the west-verging and low-angle Upar Fault system, with a detachment level in the Saldaña Formation, limits this area (Fig. 9). The Upar Fault system ends abruptly to the south, at the same point where the east-verging Teruel Fault ends. The vertical displacement of the Upar Fault decreases northward, and frontal splays of the Upar Fault system decapitates structures of the Palermo Fault system (Fig. 3).

#### 4.2 Paleomagnetism

Paleomagnetic analysis of 29 sites around La Hocha Anticline and Tesalia Syncline (Fig. 10) yielded 4 components of magnetization (Table 1) uncovered in 19 sites; the other 10 sites yielded disperse directions (Table 1). Demagnetization diagrams for the studied strata show univectorial and multivectorial paths; the latter suggests at least two events of magnetization (Fig. 11). Directions of magnetization were grouped into five components according to: (1)

their temperature/coercivity range (see Table 1 for details); and (2) the behavior of their directions before and after tilt corrections.

Directions uncovered in low coercivity (<12 mT) and temperatures (<250 °C) have dispersed directions. A component with in situ directions to the north and positive inclinations, named as component A (Table 1), were uncovered in 12 sites of both domains of La Hocha Anticline, and in Jurassic, Cretaceous and Cenozoic units (Fig. 11A). This component was uncovered at variable temperatures/coercivity ranges, and in some sites reaches up 130 mT or 660°C. After tilt correction, the dispersion of these northward directions increases (Fig. 12A).

Three characteristic magnetization components were isolated in the La Hocha Anticline and Tesalia Syncline. The first characteristic component, named component B in (Table 1), has northward declinations and very shallow positive and negative inclinations. After tilt correction, all the inclinations become shallower and increased the grouping coefficient k of the mean direction. This component was uncovered at intermediate and high temperature/coercivity ranges (Table 1 & Fig. 11B), and it was isolated in five sites of the Caballos and Potrerillos formations (Fig. 12B). The other two characteristic components were isolated in only six sites of the Saldaña Formation, and they were uncovered in high temperature/coercivity ranges until 680°C and 120 mT (in most of the cases this component included the origin, Figs. 11C & D). Component C1 corresponds to very dispersed northward directions and positive/negative inclination, isolated in two sites of the northern domain (Fig. 12C), and tree sites of the southern domain (Fig. 12D). After the two-step tilt corrections, inclinations become positive and moderate, and all the declinations are grouped to the northeast (Fig. 12C). Component C2, isolated in one site, has a north-northeastward direction with positive shallow inclination. After the two-step tilt corrections, the inclination becomes intermediate negative with similar declination (Fig. 12D).

#### **5.0 Discussion**

#### **5.1** Lateral changes in structural styles

Structural style can be interpreted as regional right-lateral strike slip faults (Chusma, San Jacinto and Matambo faults), where deformation is partitioned in shortening and strike-slip. In the southernmost La Cañada area, deformation is related to strike-slip movements. The low-dipping structural domain, bounded by high-angle faults, configures the upper segment of a

positive flower structure (Fig. 5A). These high-angle structures do not restore in a twodimensional cross-section (Rico, 2008), suggesting out-of-plane deformation.

However, we present an alternative interpretation with a thick-skinned east-verging fault system (Fig. 5B), as a possible model to explain the low-dipping structural domain observed between La Cañada and Matambo faults. As indicated before, hanging-wall and footwall cutoffs of these structures do not match in a 2D compressional style of deformation (Rico, 2008), and we prefer the former interpretation.

To the north, in La Hocha area deformation, it is related to low-angle faulting/folding cut by high-angle and out-of-sequence faults (San Jacinto and Buena Vista faults). The geometry of the La Hocha Anticline is related to the trace of the low-angle La Hocha Fault, both in the northern and southern domain. In the southern domain, the west-verging Mesitas Fault is interpreted as a backthrust of the La Hocha Fault (Fig. 6 and Fig.6B). In the northern domain, a bend in the subsurface of the symmetric geometry of the fold observed in the surface may explain the symmetric geometry of the fold observed in the subsurface.

In the Iquira and Upar areas the low-angle and east vergence faults detached in Cretaceous and Cenozoic strata are decapitated by the high-angle, basement-cored and opposite vergence Chusma and Upar Fault systems

#### **5.2 Definition of transverse zones**

Plunging folds, abrupt fault terminations, and changes in the structural styles allow us to suggest four transverse zones in the Neiva basin (Fig. 13), which limited and controlled the deformation in the structural areas defined in this work. From south to north, these transverse zones are: 1) Rio Paez Transverse zone is defined by the southern termination of the La Hocha Anticline and Tesalia Syncline, the drastic change in footwall structure of the San Jacinto Fault from overturned Cenozoic strata to gently dipping and folded Cenozoic beds, and the change in structural style from strike-slip deformation in La Cañada area to a complex relation of low- ad high angle fault systems and folds in La Hocha area. 2) La Hocha transverse zone is defined by the change in the strike of the Chusma Fault, the northern termination of the Hocha Anticline and Tesalia Syncline, and the structural step from the exposed San Jacinto Fault to the blind Buena Vista Fault. 3) The Teruel transverse zone is defined by the abrupt termination of Teruel (detachment in Villeta Fm) and El Cauchal (detachment in Guaduala Fm) faults, and

the change in the structural style, from faults verging east to opposite verging faults; and 4) The San Juan transverse zone is defined by the lineament of local sinestral displacement of the Chusma Fault, the termination of syncline folds, and the termination of the Palermo Fault system.

The location of these four transverse zones is in agreement with thickness variation/heterogeneous of beds from Cretaceous to Miocene rocks, across the faults and among the four structural areas (Fig. 4). These transverse zones formed as result of segmentation of thrust sheet motion due to the anisotropy of pre-Cretaceous and lower Cretaceous extensional structures in the southern Magdalena Valley (Sarmiento, 2001; Ramón and Rosero, 2006). If those extensional structures are perpendicular or nearly perpendicular to the maximum principal stress direction of the orogenic movement, the compressive forces cause the rocks adjacent to basement to be refracted up the fault face, and thus produce an environment favorable to the formation of tear faults and lateral ramps (Pohn, 2000) (Fig. 1). Unfortunately, 2D seismic at depth has very bad image (Fig. 6B), and very few seismic lines are perpendicular to the strike of the transverse zones. Therefore, the evidence for those transverse structures in depth relies on the lateral change of thickness of Caballos-Villeta formations (Figs. 4 to 9), and in along-strike termination of structures as decribed above.

In this work we recognize, at most, two structural styles and deformation events. The older is associated with thrusting with detachment levels in the upper Saldaña, Villeta and Guaduala formations, that generated the growth of La Hocha Anticline, the faults and related monoclinal structures to the north. The younger event is related to out-of-sequence faults with high-angle, transpresive kinematics and detachment level Saldaña Formation. This transpression event cuts and deforms the previous structures, and also controlled the thick deposition of the Honda Formation eastward of the high-angle dipping San Jacinto and Matambo faults (Fig. 4).

#### 5.3 Timing of magnetization and magnitude of rotations

Directions isolated in low coercivity/temperatures with high dispersions correspond to a viscous component. Component A, with positive inclinations and northern declinations, corresponds to the direction of the actual magnetic field. This assumption is confirmed with the increase of dispersion after tilt correction (Fig. 12A, Table 1 and Table 2). With Component B, isolated in sites of the Caballos and Potrerillos formations, the grouping

coefficient k of the mean direction increases after tilt correction. Therefore, this component is interpreted as a pre-folding magnetization event after deposition of the Potrerillos Formation (Fig. 12B and Table 2).

Component C1, with declination to the northeast and positive inclinations after the two steps of tilt correction (Fig. 12C and Table 2), indicates a magnetization in northern paleolatitudes, whereas the negative inclination of Component C2 (Fig. 12D and Table 2) indicates a magnetization in southern paleolatitudes. According to the report of other Jurassic components in the northern Andes (Bayona et al., 2005; Bayona et al., 2006; Bayona et al., 2010), we assign an early-middle Jurassic age for component C2, and a Lower Cretaceous age to the magnetization of component C1. The magnitude of clockwise rotation in the La Hocha Anticline with respect to stable point in the craton and using Component C1, is  $15.2 \pm 11.4$  in the southern domain, and  $31.7 \pm 14.4$  in the northern domain (Table 3).

## 5.4 Curved geometry of folds and timing of deformation

Paleomagnetic results in the Saldana Formation indicate clockwise rotation in both domains of the La Hocha Anticline (Table 3). The oroclinal test (Fig. 14; using Component C1) shows no relationship between the strike of strata and declination of magnetic components, rejecting the hypothesis of orocline deformation. Therefore, we interpreted the curved geometry of the La Hocha Anticline as a result of anisotropy of the basement, as indicated by the presence of transverse zones to the north and south of this anticline, as described above.

Curved geometry of faults and folds within La Hocha area are also related to right-lateral faulting of the Chusma and San Jacinto faults. Even though northern and southern domains of the Hocha Anticline rotate clockwise, the north-south geometry of the Tesalia Syncline and northern domain of La Hocha Anticline become parallel to the trace of the Chusma and San Jacinto-Buena Vista faults, respectively, as clockwise rotation and dextral movement along these faults occur (Fig. 15)

We infer a late Eocene-Oligocene age for the growth of La Hocha Anticline because the prefolding magnetization component, uncovered in the Potrerillos Formation and the abrupt change in thickness of upper Paleogene-Neogene units between hanging-wall and footwall stratigraphy of the San Jacinto Fault (Fig. 4). Conglomeratic units of the Tesalia and Doima

formations have been interpreted as syn-orogenic units in other areas of the Upper Magdalena Valley Basin (e.g. Amézquita and Montes, 1994; Montes et al., 2003; Ramón and Rosero, 2006). Strike-slip deformation also controlled localized deposition and deformation of the Honda Formation in the footwall of the San Jacinto Fault, and in the core of the Tesalia Syncline (Morales et al., 2001; Marquinez et al., 2002). The geologic map shows deformed beds of Honda Formation, suggesting a last pulse of deformation after the middle to late Miocene.

#### **6.0** Conclusions

The paleomagnetic and structural analysis in the Neiva basin allow us to propose four transverse zones, whose strike is almost perpendicular to the strike of regional structures. The curved shape of the Tesalia and La Hocha folds, as well as the clockwise rotation in both domains of the La Hocha Anticline, are related to pre-existing configuration of the basin and strike-slip deformation of the Chusma and San Jacinto faults. Those transverse zones are the surface expression of buried structures (basement anisotropy), which also control the type of deformation inside each structural area. Two deformation events, with different style of deformation, were identified. An Eocene-Oligocene event of thrusting with detachment levels in the upper Saldaña, Villeta and Guaduala formations generated the growth of La Hocha Anticline. The late Miocene event is related to out-of-sequence faults with high-angle, transpresive kinematics; this event cuts and deforms the previous structures, drove clockwise rotation of the La Hocha Anticline, and controlled localized deposition of the Honda Formation.

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#### FIGURE CAPTIONS

Figure 1. Map view of transverse zones in compressional settings.

**Figure 2.** Regional location of the Southern Upper Magdalena Valley (Neiva Basin) (Modified from Ramón and Rosero, 2006)

**Figures 3 A & B.** Geologic maps with location of the major structures, structural domains and structural cross-sections constructed for each structural area.

**Figure 4.** Generalized stratigraphic column of the Southern Upper Magdalena Valley Basin (Neiva Basin), showing position of detachment levels and stratigraphic thickness determined for Cretaceous and Cenozoic units for different structural domains.

**Figure 5A.** Structural cross-section of La Cañada Area, Strike-slip interpretation (Modified from Rico, 2008). Note thickness variations across faults.

**Figure 5B.** Structural cross-section of La Cañada Area with an alternative model for deep structure, reverse faulting interpretation. For conventions see Figure 5A.

**Figure 6.** Structural cross-section of the southern domain of La Hocha area. Note thickness variations across faults (Modified from Jiménez, 2008). For conventions see Figure 5A.

**Figure 6B.** Two-dimensional seismic profile (see figure 3A for location) showing the depth structure of La Hocha Anticline in the Southern Domain.

**Figure 7.** Structural cross-section of the northern domain of La Hocha area. Note thickness variations across faults (Modified from Jiménez, 2008). For conventions see Figure 5A.

**Figure 8.** Structural cross section of the Iquira area. Note thickness variations across faults. For conventions see Figure 5A.

**Figure 9.** Structural cross-section of the Upar area. Note thickness variations across faults. For conventions see Figure 5A.

**Figure 10.** Geologic map of the La Hocha Anticline and Tesalia Syncline, with location of paleomagnetic sites.

**Figure 11.** Orthogonal diagrams of demagnetization of representative samples before tilt correction. Full (open) symbols in Zijderveld plots represent projections onto the horizontal (vertical) plane. NRM = Natural remanent magnetization.

**Figure 12.** Equal-area plots at different ages and domains showing tilt-corrected directions of paleomagnetic Components A and C. Solid (open) symbols represent positive (negative) inclinations.

**Figure 13.** Regional Map of the Southern Upper Magdalena Valley (Neiva Basin) with the location of the four transverse zones proposed in this study, and paleomagnetic declinations showing different magnitude of clockwise rotation between domains of La Hocha Anticline. **Figure 14.** Oroclinal test for 5 sites of Component C1 isolated in the Saldaña Formation. A reference strike ( $S_0=0$ ) and reference declination ( $D_0=0$ ) was used for the Calculation of declination deviations (D-D<sub>0</sub>) and strike deviations (S-S<sub>0</sub>) for the strike test of Schwartz and Van der Voo (1983). R2= correlation coefficient, and S= slope. Error bars for declination data are the respective a95/cos(I) values, R<sup>2</sup>= correlation coefficient, and m= slope. **Figure 15.** Illustration (not a scale) showing the clockwise rotation of La Hocha area related to dextral movements of Chusma, Buena Vista and and San Jacinto Faults.

#### TABLE CAPTIONS

**Table 1.** Statistical parameters of mean-site directions uncovered in 29 sites analyzed in the Neiva Basin. DD/D=dip direction/dip angle; KrDD/KrD= corrected Cretaceous bedding for Jurassic beds; N/n=total specimens/specimens used for mean calculation; D=Declination; I=Inclination; k=the Fisher (1953) precision parameter; a95=half-angle of 95% confidence about the mean for sites.

**Table 2.** Statistical parameters of mean-site directions uncovered for each component in La

 Hocha area. Abbreviations as in Table 1

**Table 3.** Rotations calculated using the characteristic components C1 (D, I) in the southern and northern domain of La Hocha Anticline, relative to an arbitrary point in the stable craton (4° N, 72°W). D° = declination,  $D_e$  = declination error defined as a95/cos(I), R° = Rotation,  $R_e$  = Rotation error, , I° = Inclination, ,  $I_e$  = Inclination error defined as a95, F = flattening and  $F_e$  = flattening error.





Figure 2. Jimenez, et al.



Figure 3A. Jimenez, et al.



Figure 3B. Jimenez, et al.



Figure 4. Jimenez, et al.



Figure 5A. Jiménez, et al.



Figure 5B. Jiménez, et al.





Figure 6B. Jiménez et al

















B. LH3-c2 Caballos Fm. Northern domain - Western flank



D. LH8-f Saldaña Fm. Southern domain - Western flank



Figure 11. Jimenez, et al.







Figure 12. Jimenez, et al.



Figure 13. Jimenez, et al.



B. Deformation of the La Hocha Anticline and Tesalia

Sycline as a single block bounded by Chusmas and San

Jacinto fault systems, with regional clockwise rotation



A. Fold geometry and magnitude of clockwise rotation of the La Hocha Anticline ocurred as indepented blocks; strike of Tesalia Syncline an Pacarni Faults follow and N-S trend

			Destations		1		In situ			Ti	lt 1	Saldana	Tilt 2		[		
Site	Unit	N/n	(DB/B)	Component	Interv	/al	Dec	Inc	k	295	Dec	Inc	Bedding	Dec	Inc	Interpretation	Lab
			(66/6)				Dec	inc	n	a35	Dec	inc	(DB/B)	Dec	IIIC		
Nothern domain																	
1 11 1 9 2	Soldoão	7/6	Vestern flar	1K ^	2	120 mT	EG	171	04 AE	7.2	252 E	10.6	0E/44	65	15	Actual field	Buonoo Airoo
	Sdiudiid	7/5	75/5	C1	100	120 mT	23	47.8	38.98	12.4	335.5	49.6	03/44	26.4	44.3	Saldaña-Cretaceous	Buenos Aires
	Caballos		267/20														
	Bedding		201133														
LH3	Caballos	6/5	267/39	В	350°C	9450	11.4	4.4	113.25	7.2	5.5	12.5				Pre-fold	Buenos Aires
LH4	Caballos	6/3	207/39		150	560°C	92.7 292.5	-47.0	49.50	13.2	90.6 291.5	-9.2				Disperse directions	Buenos Aires
		6/3		В	600	660°C	167.9	4.4	371.27	6.4	172.7	9.1				Reverse pre-fold?	
LH5	Caballos	4/4	267/39		0	2mT - 600º	52.7	-36.8	186.56	6.7	60.1	-2.8				Disperse directions	Buenos Aires
		4/3		В	9	130mT	356.7	-3.1	24.94	25.2	358	-2.6				Pre-fold	
LH6&7	Villeta	7/4	255/27		0-3mT	50°C-39m	359.4	23.4	49.12	13.2	344.2	28.4				Actual field	Buenos Aires
1 144	Saldaña	7/5	202/28	A	640-25m1	12mT	300.9	37.1	23.13	16.2	290.6	15.3	66/12	84.1	30.8	Disperse directions	See Boule
L1144	Jaiuaria		292/28		15	60 mT	96.5	25	18.66	13.2	89.1	51.5	00/13	84.4	39.4	Disperse directions	Sau Faulu
			292/28		60	9070	100.1	26.7	7.66	29.5	93.7	53.8		87.7	42	Disperse directions	
LH33	Saldaña		150/20		0	12.5 mT	97.4	44.1	1.56	180	108.6	30.3	111/44	108.8	-13.7	Disperse directions	Sao Paulo
			150/20		12.5	20mT	123	17.1	1.7	180	124.3	-0.8		129.4	-43.3	Disperse directions	_
			150/20		25	9025	107.9	20	13.25	35.3	110.8	4.7		110.7	-39.3	Disperse directions	
11146	Caldaãa		Plunge		0	45 m T	22.0	44.4	2.00	100	01.0	20.0	050/04	00.0	20.0	Distance allowed and	Cee Deule
LH40	Saluana		50/36		15	25mT	339.4	42.4	4.38	67.9	21.3	-20.9	358/21	20.0	-39.0	Disperse directions	Sao Paulo
			50/36		50	9060	290.7	47.2	285.43	14.8	335.3	52.1		341.7	32.2	undefined	
I H47	Saldaña		50/38		0	20mT	204.2	-3.1	124 89	6	199.7	30.7	26/38	191.3	68.2	Disperse directions	Sao Paulo
	Guidania		50/38		20	60mT	248.1	1.1	5.6	31.1	252.9	36.9	20/30	290	54.1	Disperse directions	Sao i auto
			50/38		60	9070	263.4	9.7	7.49	29.9	274.9	39.8		309.8	42.4	Disperse directions	
	Usperse directions																
1 11 17	Caballas	0/0	72/22		00T (5000				70.50	7.0	40.0	40.0			_	A short Cold	
	Cabalios	6/6	13/32	A	60m1-450°C	9120-660°C	14.4	-0.2	72.53	7.9	10.3	-16.2	457/00			Actual field	Buenos Aires
LILIO	Saluana	7/5	110/44		0	9mT	172.3	8.7	80.7	8.6	-		157/29			Disperse directions	Buenos Aires
		7/4			150	580°C	136	29	11.72	28	125.7	11.6		125.5	-13.3	Disperse directions	
	Dedder	7/5	70/00	C1	70mT-540°C	9070-600°C	16.4	25.9	17.39	18.9	23.9	6.2		30.3	25.1	Saldaña-Cretaceous	
	Bedding		13/32														
		Southerr	n domain														
		v	lestern flar	ık													
LH8	Saldaña	6/4	332/42	A	9-100	30mT-200°	16	29.5	47.58	13.5	13.2	-23	157/29	10	-3.1	Actual field	Buenos Aires
		6/4		C2	110mT	9130	8.1	6.3	61.42	11.8	26	-45		13.8	-27.1	Saldaña- Jurassic	
	Capas		334/66														
LH9	Caballos	6/6	311/34	Α	600	680°C	349.4	10	103 13	6.6	350.7	-16.7				Actual field	Buenos Aires
LH36	Saldaña	0/0	290/35	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	0	30mT	87.3	13.3	24.07	19.1	78.1	44.7		121.7	39.5	Disperse directions	Sao Paulo
			290/35		30	9060	119.6	-13.1	40.47	12.2	120.1	21.5		127.2	-1.8	Disperse directions	
LH38	Saldaña		320/28		0	2.5mT	342.2	-1	3.27	180	345	-26.8	275/8	349.1	-29.2	Disperse directions	Sao Paulo
			320/28		2.5	25m I	313.4	18.5	119.43	11.3	513.0	-9.4		314.8	-15.6	Disperse directions	
1 H 30	Saldaña		271/36		30	9030 15mT	240	-31.9	11.75	23.1	243.1	-64		237.6	9.0	Disperse directions	Sao Paulo
LINGO	ourdund		271/36		15	30mT	267.2	26.4	18.21	18.4	267.5	-9.5		230.5	33.5	Disperse directions	ouo r uulo
			271/36		30	9100	275.9	32	15.9	19.8	275.1	-3.9		220.3	37.9	Disperse directions	
			Eastern fl	ank													
LH15	Saldaña	8/7	135/75		0	12mT	329.6	10.1	10.14	19.9			315/55			Disperse directions	Buenos Aires
		8/8		A	3-0	20mT-300°	12.2	0.9	17.13	13.8	68.2	23.9		36.5	31.8	Actual field	
		8/8		C1	70mT-450	9120-580	6.1	-12.2	9.9	18.5	62	37.3		19.5	32.6	Saldaña-Cretaceous	
	Capas		135/130	Capae Invertid	26												
LH31	Saldaña	5/5	64/76	oupus inventio	0-100	2mT-250°	11.1	8.7	11.38	23.7			50/68			Disperse directions	Buenos Aires
		5/5			15-450	20mT-540°	71.2	0.6	33.92	13.3	66.1	-15.1		119.5	-73.8	Disperse directions	
		5/4		C1	120mT	9120	315.6	9.4	115.75	8.6	314.8	50.4		7.9	20	Saldaña-Cretaceous	
LH32	Saldana	5/5	64/76		0	100mT	348.2	50.2	4.21	42.4	02.5	24.0	50/68	140	50.4	Disperse directions	Buenos Aires
		5/4		C1	15 50mT	9100	304.7	9.3	55.69	12.4	208.8	-21.0		3.0	-50.1	Saldaña-Cretaceous	
	Bedding	0/4	407/44	01	00111	5100	004.7	1.5	00.00	14.7	200.0	47.0		0.0	00.2		
	Caballos		137/41														
LH16	Villeta	8/5	20/69	A	0-3mT	400-39mT	346.8	9.2	34.21	13.3	329.5	-45.6				Actual field	Buenos Aires
LH30	Villeta	4/4	196/44	A	600	660°C	349.2	7.3	801.28	3.2	336.8	44.9				Actual field	Buenos Aires
LH19	Bache	6/0	102/86		0	EmT	222.2	E1 0	0.04	190	164.0	26.4		150.0	2.7	Disperse directions	Buenos Aires
LI143	Jaiuaria		120/61		5	30mT	305.1	15.1	24.5	15.8	319.8	75.3		128.7	66.5	Disperse directions	Sau Faulu
			120/61		30	9025	355.5	22.1	1.36	125.8	35.5	39.9		65.6	34.5	Disperse directions	-1
Syncline domain																	
Eastern flank																	
LH10A	Guaduala	3/3	264/28		500	640°C	353.3	13.9	25.78	24.8	346.8	11.9		└──┤		Disperse directions	Buenos Aires
LH10B	Bache	3/3 6/0	302/34		00-0	∠0111-200°	340.7	34.1	∠ე.85	24.ŏ	330.2	21					Buenos Aires
LH12	Potrerillo	6/4	305/28	A	100	580°C	341	35.1	8,23	34.1	334.4	11.4				Actual field	Buenos Aires
		6/2		В	350°C	9540	10.3	23.3	92.19	26.3	2.8	9.7				Pre-fold	
	Western flank																
LH13	Potrerillo	6/5	95/86	A	3-0	00mT-500°	357.8	9.9	16.41	19.5	14.5	7.8			-	Actual field	Buenos Aires
1 1.14 4	Doché	6/4	100/54	В	100mT-300°C	9100-620°C	3.4	-0.4	7.7	35.4	4.5	1.6				Pre-told	Duese Alars
LH14	Bache	v/4	100/51		500	640°C	211.1	51.9	39.71	14.8	1/4.6	34.8		I		Disperse directions	Buenos Aires

Table 1

#### Table 2

Component	linit	(N/m)								
Component	Onit	(11/11)	Dec	Inc	k	a95	tilt			
Actual field	All	sites= 22/12	357.9	16.2	23.96	9.1	In situ			
			356.8	4	5.3	20.8	tilt correction 1			
Pre-fold	Caballos and Potrerillos	sites=16/5	1.8	3.9	29.63	14.3	In situ			
			0.8	2.4	62.33	9.8	tilt correction 1			
Saldaña-C1										
	Nothern domain									
LH1&2-LH18	Saldaña	sites= 2/2	19.3	37	17.34	11.9	In situ			
		specimens=14/10	4.8	30.3	5.62	22.4	tilt correction 1			
			28.5	34.8	19.04	11.4	tilt correction 2			
Southern domain										
LH15-31-32	Saldaña	sites= 4/3	336.4	-1.52	5.34	17.6	In situ			
		specimens=24/16	9.8	60.5	3.7	22.3	tilt correction 1			
			12	28.9	16	9.5	tilt correction 2			
Saldaña-C2										
LH-8	Saldaña	sites= 6/2	8.1	6.3	61.4	11.8	In situ			
		specimens= 13/5	26	-45	61.4	11.8	tilt correction 1			
			13.8	-27	61.4	11.8	tilt correction 2			

# Table 3

Structural domain	D°	D <sub>e</sub> (°)	Rº	R <sub>e</sub> (°)	I (°)	l <sub>e</sub> (°)	F (°)	F <sub>e</sub> (°)
Nothern domain								
Saldaña C1	28.5	13.9			34.8	11.4		
craton	356.8	3.6			16.4	3.5		
			31.7	14.4			-18.4	11.9
								(
Southern domain								
Saldaña C1	12	10.9			28.9	9.5	<b>_</b>	
craton	356.8	3.6			16.4	3.5		Y
			15.2	11.4			-12.5	10.1

#### Highlights

Multiple analyses were used to determine the origin of curved folds.

Analyses include mapping structural, and paleomagnetic studies.

Tranverse zones are defined by the along-strike termination of faults and folds.

The Curved shape of folds is related to anisotropy of the basement

The regional strike-slip faults cause the clockwise rotations in La Hocha Anticline.