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Journal:	<i>The Leading Edge</i>
Manuscript ID	Draft
Manuscript Type:	December 2021: Latin America
Date Submitted by the Author:	n/a
Complete List of Authors:	Galindo, Pedro; Ecopetrol; Imperial College London, Department of Earth Science and Engineering Loneragan, Lidia; Imperial College London, Department of Earth Science and Engineering
Keywords:	seismic, strike-slip , faults, 3D, interpretation
Subject Areas:	Interpretation Methods and Interdisciplinary Studies, Seismic Amplitude Interpretation

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Sigmoidal normal faults and evidence for vertical-axis block rotation in an oblique convergent margin: A 3D-seismic example offshore Colombia

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ABSTRACT

Sigmoidal fold and fault geometries are typical kinematic indicators of strike-slip fault zones. We document km-scale, normal faults with sigmoidal plan-view geometries within the dextral pull-apart Bahia Basin, at the rear of the obliquely convergent South Caribbean Deformed Belt, offshore Colombia. Using three-dimensional seismic reflection data calibrated to wells, closely spaced, low-displacement, planar normal faults are mapped within the Miocene strata. A series of seismic horizontal (time) slices and computed seismic attributes are used to interpret the 3D configuration of these faults. The closely spaced faults display an E-W trend, with a progressive rotation into a NW-SE trend. In map view, the fault traces curve towards their tips describing a sigmoidal-Z geometry that terminate at discrete NE-SW trending fault zones. The structures observed may correspond to either tension fractures (T) which form theoretically at 45°, or antithetic shear fractures (R') with normal displacement formed at 50°-70° to the boundaries of a dextral shear zone. These scenarios lead to a clockwise block rotation of between 20° and 40° within the shear zone. This study shows the first example of vertical-axis block

rotations observed offshore in the western end of the South Caribbean margin and is an important example of the use of 3D seismic data to identify rotations where paleomagnetic studies are not available.

INTRODUCTION

En-echelon and sigmoidal structures are typical kinematic indicators of strike-slip tectonics and occur at cm- to the km-scale. A classic example are sigmoidal veins that form as rotated tensile fractures during simple shear (e.g. Ramsay and Huber, 1983; Bons et al., 2012); but sigmoidal and en-echelon normal faults, folds and thrusts are also common features of strike-slip basins (e.g. Richard et al., 1995; Waldron, 2005; Mann, 2007; Dooley and Schreurs, 2012; Allen and Allen, 2013). In simple shear deformation, the maximum compressive stress (σ_1) acts at 45° to the boundaries of the shear zone (Fig. 1). In response, tension fractures (T) and normal faults form parallel to the maximum principal compression and perpendicular to the minimum stress. As a result of the continuous deformation (Fig. 1B-D), and because the orientation of the instantaneous stretching axis remains fixed with respect to the boundaries of the shear zone, new faults continuously form at 45°, and the early formed faults rotate and amalgamate with the new ones creating a sigmoidal shape (Fig. 1E) (e.g. Ramsay and Huber, 1983). This passive rotation of the older segments of the fault implies that the blocks bounded by these faults have also been rotated in response to the overall shear sense (e.g. Freund, 1974; Peacock et al., 1998; Waldron, 2005). Analogue experiments investigating strike-slip faulting, have identified the development of sigmoidal faults as a kinematic indicator of block rotation, where the sigmoidal curvature define the sense of rotation. Hence, sigmoidal Z shapes of normal faults and veins are indicative of clockwise rotation, while sigmoidal S shapes indicate counterclockwise rotation (Freund,

1974; Gapais et al., 1991; Schreurs, 2003). At larger scales, vertical-axis block rotation has been documented in strike-slip basins around the globe and can be detected by paleomagnetic (e.g. Ron et al., 1984; Luyendyk et al., 1985; Lewis and Stock, 1998; Chen et al., 2002), geodetic (e.g. Allmendinger et al., 2007; McCaffrey et al., 2007; Wallace et al., 2009) and seismologic (e.g. Nicholson et al., 1986a, 1986b; McCaffrey, 2005; Wallace et al., 2007) methods.

At oblique convergent plate boundaries both observational and theoretical studies have shown that because of strain partitioning the active strike-slip faults, which take up a significant proportion of the strike-parallel motion, occur some distance away from the active subduction zone towards the rear of the system (e.g. Fitch, 1972; Beck, 1983; McCaffrey, 1992; Beck et al., 1993; Yu et al., 1993; Teyssier et al., 1995). Mechanical analyses such as that of Platt (2000), show that localized deformation is expected at the rear of the wedge along a discrete zone of strike-slip deformation where vertical-axis block rotation, amongst other structures, might be expected to occur. To date, examples of block rotation in strike-slip zones at the rear of marine accretionary-prisms have yet to be documented. Here we use high-quality, post-stack, time migrated 3D seismic reflection data to describe a unique example of offshore sigmoidal-normal faults that imply vertical-axis block rotation in a zone of strike-slip deformation at the rear of the present-day accretionary prism, offshore northern Colombia.

Tectonic setting

The southern margin of the Caribbean has been widely recognized as region of oblique subduction and strain partitioning (e.g. Avé Lallemant, 1997; Escalona and Mann, 2011) with strike-slip deformation at the rear of the accretionary wedge occurring along offshore Venezuela (e.g. Beardsley and Avé Lallemant, 2007; Gorney et al., 2007; Audemard and Castilla, 2016) and

Colombia (Gomez, 2001; Galindo, 2016; Galindo and Lonergan, 2020; Vence and Mann, 2020).

The study area lies at the western end of the Oca fault within the dextral Bahia Basin located in the NW corner of South America, offshore Colombia out-board of major, regional strike-slip faults, which define the geometry of the NW corner of South America (Fig. 2A). The evolution of Bahia Basin has been described recently by Galindo and Lonergan (2020). It initially formed as a dextral transtensional basin from late Oligocene to Late Miocene times, most likely as the offshore extension of the E-W trending Oca fault (Fig. 2A) and was subsequently inverted during Plio-Pliocene times due to transpression and the northward movement of the Santa Marta massif. Furthermore, pervasive mud volcanism is also present in the area, whose source is interpreted as overpressured shales of Oligocene age (Galindo and Lonergan, 2020).

The Bahia Basin is located ca. 60 km behind the toe of the South Caribbean Deformed Belt. This is an area of complex deformation between the offshore-compressional folding and the onshore large strike-slip systems that dominate the NW corner of South America. The South Caribbean Deformed Belt is the accretionary prism formed along the convergent margin between the Caribbean and South American Plates, offshore Colombia and Venezuela (Ladd and Truchan, 1983; Ladd et al., 1984). The accretionary prism is growing in response to the ESE-directed subduction of the Caribbean Plate at a rate of ca. 20 mm/yr (e.g. Trenkamp et al., 2002; Symithe et al., 2015; Mora-Páez et al., 2019). The sediments within the prism are interpreted as the offscraping of sediments from the subducted crust, and the sediments deposited on top of the prism by prograding-deltaic systems coming from the continent (e.g. Magdalena River; Fig. 2A). However, the anomalous high thickness of the Caribbean crust and the low angle of subduction, prevent the formation of a typical bathymetric trench in front of the wedge as occurred in other areas of oceanic plateau subduction (Mann and Taira, 2004; Kroehler et al., 2011). The age of

the South Caribbean Deformed Belt is still a matter of debate and may respond to regional and local deformation processes. Regionally, Müller et al. (1999), propose a NW-SE convergence between North and South America since early Eocene times resulting in 200-400 km of shortening. Locally, east-west plate convergence is attributed to the collision of the Panama Arc since middle to late Miocene times (Duque-Caro, 1979; Montes et al., 2012a, 2012b, 2015). The relative eastern movement of the Caribbean Plate forms dextral strike-slip systems along the northern margin of the South American Plate (e.g. Audemard and Castilla, 2016), where the W-E Oca-Ancon-El Pilar Fault System constitutes the main fault system along Colombia and Venezuela (Audemard, 1996) (Fig. 2A). The western segment of this dextral fault system (i.e. the Oca Fault), forms the sharp-northern boundary of the Santa Marta Massif, crosses the Guajira Peninsula, and continues into the northern area of the Maracaibo Gulf. The western end of the Oca Fault System is interpreted at different splays within the NW corner of the Santa Marta Massif (Audemard, 1996) and an offshore splay that causes the development of the Aguja Canyon (Restrepo-Correa and Ojeda, 2010). The Bahia Basin is located offshore in front of the NW corner of the Santa Marta Massif, which is also the termination of the NW-SE trending, left-lateral Santa Marta-Bucaramanga Fault (Fig. 2A).

Data and methods

A high-quality, pre-stack, time migrated (PSTM) seismic volume covering an approximate area of 1500 km², was used for this study. It consists of 1196 lines (NE-SW) at a spacing of 25 m, and 4056 traces (NW-SE) at a spacing of 12.5 m. In depth, the volume has a record length of 7 seconds TWT (ca. 8 km), with a sample rate of 4 ms. The seismic volume has an average frequency content of 30 Hz which gives a resolution of ca. 20 m in the vertical and ca. 25 m of

horizontal resolution. Biostratigraphic data from one well within the seismic volume has allowed us to assign late Oligocene to Recent ages to the stratigraphy (Fig. 2B). Time slices and seismic profiles sections are used in order to fully characterize the complex tridimensional configuration of the deformation. Furthermore, volume-based seismic attributes such as coherency (e.g. Marfurt et al., 1998) and spectral decomposition (e.g. Partyka et al., 1999) are also included to facilitate the interpretation of fault planes.

RESULTS

Seismic expression and structure of the Bahia Basin

Several unconformities can be interpreted in the seismic data, including regional unconformities that divide the basin into a series of tectono-stratigraphic units. The most important unconformity that can be mapped continuously through the area of the survey is the upper Miocene to lower Pliocene unconformity. The time-structure map (Fig. 3A) shows a complex structural configuration with the presence of several highs and lows and a range in time between 1400 ms and 5000 ms (TWT). This surface shows a broadly triangular basin bounded by faults A, C and D (Fig. 3B). Fault A, like the trend of the structures within the thrust belt, strikes NE-SW, almost parallel with the limits of the 3D seismic volume, and continuing the trend of the coastline and shelf break present towards the SW (Fig. 2A). This fault is identified by the alignment of several mud volcanoes that erupt on the seabed and the thickening towards the south of Plio-Pleistocene sediments within the Bahia Basin (Fig. 2A-B). The E-W trending Fault C corresponds to the southern boundary of the basin and displays a similar trend to the Oca Fault System further to the east. Towards the east, the N-S trending Fault D is interpreted as a reverse fault related to the northern termination of the Santa Marta–Bucaramanga Fault (Galindo and Lonergan, 2020).

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3 Within the basin, the Bahia Fault is the most important structure. The NE-SW cross-basinal fault
4 is composed of three left-stepping segments (Bs, Bc, Bn; Fig. 3), which are the south-eastern
5 boundary of structural highs located in the footwall side of the fault (southern-SH, central-CH
6 and northern highs-NH in Fig. 3B). On the south-eastern side of the Bahia Fault a main
7 depocenter area is formed, within which ca. 4 s TWT (ca. 4.6 km) of Neogene sediments were
8 deposited.
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19 **Structures below the upper Miocene to lower Pliocene unconformity**

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21 The main observation that defines the interpretation of the upper Miocene to lower Pliocene
22 unconformity is the strong difference in the seismic character below and above the unconformity.
23
24 Below the unconformity the imaging is less clear and a high density of low displacement normal
25 faults disrupts the seismic response, whereas above the reflections are clearer, continuous and
26 rarely affected by faulting (Fig. 4). Beneath the upper Miocene to lower Pliocene unconformity
27 the footwall of the Bahia Fault is deformed by a large number of closely spaced, low-
28 displacement, extensional faults. The faults have a planar geometry, dip between 45° and 60°,
29 and affect just the Miocene section deforming ~ 1000 m? of stratigraphy (Fig. 4). A series of
30 seismic time slices and seismic attributes are used to interpret the 3D configuration of these
31 faults (Fig. 5). The images show a series of closely spaced E-W trending faults, with a
32 progressive rotation towards the north to a NW-SE trend. In map view, the fault traces curve
33 towards their tips describing a sigmoidal-Z geometry. The curvature of the faults is particularly
34 well imaged in the spectral decomposition images (e.g. Fig. 5C). The sigmoidal faults terminate
35 at discrete NE-SW trending fault zones (i.e. Faults Z, Z' and Z'' in Fig. 5D), which are sub-
36 parallel to the regional Fault A and the Bahia Fault.
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DISCUSSION

Interpretation of sigmoidal-Z geometries

The geometry and location of the sigmoidal-Z normal faults are kinematic indicators of a dextral strike-slip shear zone occurring between the Fault A and the Bahia Fault and suggest a clockwise rotation of the northern block within the Bahia Basin. In map view, normal faults are expected to occur in simple-shear zones at 45° from the margin, although this value may decrease or increase in areas of either transtension or transpression, respectively (Fig. 1A) (Sanderson and Marchini, 1984). Experiments of analogue modelling that use layered dry-quartz sand and glass powder over a viscous-detachment level has been performed to analyze the distributed strain within a dextral strike-slip shear zone (Schreurs, 1994, 2003). Similarly, the blocks within the Bahia Basin may present the Oligocene shale section as a viscous detachment. However, in these experiments sigmoidal faults are formed at high angle against the master faults (as antithetic Riedel shears, R' ; Fig. 1A) and correspond to the boundaries of rotated blocks. These experiments show the development of dextral faults subparallel to the boundaries of the shear zone, and sinistral strike-slip faults at high angles (ca. 50° - 70°) to the master-dextral strike-slip faults. With increasing strain, the sinistral faults rotate and propagate laterally, acquiring a sigmoidal-Z shape in map view. The rotations about vertical axes of the antithetic faults and the blocks in between create space problems that respond as small dip-slip components that change along strike. Hence, these faults show a small normal displacement at the end, no dip-slip displacement at the center, and a small inverse displacement at the opposite end of the sigmoidal fault, describing them as scissor faults (Schreurs, 2003). In the northern block of the footwall of the Bahia Fault, Fig. 3 shows the presence of fault zones subparallel to the boundaries of the

shear zone (i.e. Faults Z, Z', Z''), together with sigmoidal-Z faults at a high angle to the Bahia Fault. These sigmoidal faults also illustrate a small left-lateral displacement (see blue horizon on Fig. 5E) similar to the results of the analogue modelling, supporting that these formed as antithetic faults (R' shears). However, the faults display a continuous normal displacement along the strike of the faults, different to that predicted by analogue models.

In summary, the presence of sigmoidal Z geometries in map view is a typical kinematic indicator of vertical-axes clockwise rotation in a dextral strike-slip shear zone. However, in comparison to the theoretical structures formed within a shear zone, the structures observed in the northern block of the footwall of the Bahia Fault may correspond to normal faults that form parallel to tension fractures (T) formed at 45° to the Bahia Fault, or antithetic shear fractures (R') formed at 50°-70° to the boundaries of the shear zone. These possible scenarios lead to different amounts of block rotation within the shear zone. If the faults initially formed as normal faults, the current presence of NW-SE faults proposes a maximum 45° clockwise rotation, while antithetic shear fractures would support a clockwise rotation between 20° and 40°.

Implications for the tectonics of NW South America

This deformation was occurring in the context of oblique subduction along the South Caribbean Deformed Belt since Miocene times. A regional section (Fig. 2B) shows that whilst thrusts dominate the frontal parts of the accretionary prism, the deformation style significantly changed at the rear of the wedge in the area of the Bahia Fault and basin. Our results show that the deformation at the rear of the wedge is dominated by complex strike-slip tectonics and provides evidence of partitioning of deformation associated with the oblique subduction of the Caribbean Plate (Fig. 6). Strain partitioning between strike-normal motion at the frontal part of the

forearc/accretionary prism near the subduction zone and strike-parallel motion towards the rear of the accretionary wedge has been observed in many subduction zones worldwide (e.g. Fitch, 1972; McCaffrey, 1992; Yu et al., 1993) and is predicted from both theoretical and analogue models (e.g. Platt, 2000; McClay et al., 2004). Furthermore, given the relative sense of movement of the subducted plate (i.e. Caribbean) and its angle of obliquity with respect to the trend of the accretionary front (ca. 50°), mechanical models of accretionary viscous wedges predict the possible development of different styles of strike-slip deformation, including rotations about vertical axes (Fig 10 in Platt, 2000), as observed within the northern block in the footwall of the Bahia Fault (Fig. 6).

In the Miocene the angle of obliquity between the direction of subduction and strike of the frontal toe of the accretionary prism may have been different from that observed today. However a variety of studies including the use of tomography (van der Hilst and Mann, 1994; Miller et al., 2009; Bezada et al., 2010a, 2010b; van Benthem et al., 2013), GPS measurements (Weber et al., 2001; Trenkamp et al., 2002; Symithe et al., 2015), seismology (Corredor, 2003; Cortés et al., 2005), field studies (e.g. Bayona et al., 2010; Cardona and Ojeda, 2010; Lara et al., 2013; Cardona et al., 2014) and tectonic plate restorations (e.g. Müller et al., 1999; Pindell and Kennan, 2009; Bochman et al., 2014; Montes et al., 2019) have supported the model of an eastern movement of the Caribbean Plate relative to South America since the Miocene, which implies an angle of obliquity at least equal to that observed today. Moreover, the obliquity is expected to be higher in the location of the Bahia Basin where the South Caribbean Deformed Belt curves to the east in comparison to regions south of the Magdalena Fan where the accretionary prism forms a higher angle with the Caribbean Plate (i.e. Sinu Fold Belt; e.g. Flinch, 2003). Clockwise vertical-axes block rotations have also been documented onshore in Venezuela and Colombia from

several paleomagnetic studies (summarized by Audemard, 2009; and Montes et al., 2010, respectively) as a result of the complex interaction of multiple tectonic blocks during the evolution of the NW corner of South America. Hence, the example of rotations that we document in the footwall of the Bahia Basin is the first example of rotations observed offshore in the region. Moreover, this is an important example of how 3D seismic data may help to identify vertical-axes rotations where paleomagnetic studies are not possible.

ACKNOWLEDGMENTS

This study is part of the PhD project completed by P. Galindo at Imperial College. We thank the ‘Departamento Administrativo de Ciencia, Tecnología e Innovación’ (COLCIENCIAS) and their “Francisco José de Caldas” Scholarship Programme, providers of the funding for this research. Thanks to ECOPETROL S. A. for providing the data used for this research, and for the permission to publish these results. Halliburton Software and Services, is acknowledged for providing the Landmark software used to interpret the seismic data under a university software grant to Imperial College.

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FIGURE CAPTIONS

Figure 1. Mechanism to generate sigmoidal-Z normal faults within a dextral shear zone. A) Structures formed in a simple-dextral shear zone; faults and folds form at 45° to the boundaries of the zone. Note the change in the strike of the structures in transpressional or transtensional settings. B) Incremental strain at $\Psi=30^\circ$. C) Incremental strain at $\Psi=45^\circ$. D) Incremental strain at $\Psi=60^\circ$. E) Sigmoidal normal faults as a result of the incremental strain within a simple-dextral shear zone.

Figure 2. A) Location of the study area in the NW corner of South America. The Bahia Basin is in front of the NW corner of the Santa Marta Massif, at the end of two regional strike-slip fault systems: the EW trending Oca Fault System (OFS), and the NW-SE trending Santa Marta-Bucaramanga Fault (SMBFS). Faults A, B, C and D are the main faults observed in the Bahia Basin. B) NW-SE cross section showing the South Caribbean Deformed Belt and the Bahia Basin towards the rear of the accretionary prism (modified from Galindo and Lonergan, 2020).

Figure 3. A) Upper Miocene to lower Pliocene unconformity time-structure map. The NE-SW trending Bahia Fault compartmentalizes the basin and separates the high blocks in the NW (SH=Southern High, CH=Central High, NH=Northern High) from the main depocenter in the SE. The blue box highlights the location of the focus area in the northern high. The contour interval is 100 ms TWT. B) Upper Miocene to lower Pliocene unconformity structure map. Faults A, C and D form the boundaries to the Bahia Basin. Bahia Fault is formed by three main segments (Bs=Bahia south, Bc=Bahia central, Bn=Bahia north). Note

the North position towards the upper right corner (modified from Galindo and Lonergan, 2020)

Figure 4. Uninterpreted (above) and interpreted (below) S-N seismic section across the northern high of the Bahia basin showing the closely spaced, low-displacement, extensional faults. Colored horizons correspond to main unconformities interpreted within the basin: in green, UMLPU (Upper Miocene to Lower Pliocene Unconformity); in blue, MMU (Middle Miocene Unconformity); in magenta, UOLMU (Upper Miocene to Lower Miocene Unconformity); in orange, MEU (Middle Eocene Unconformity).

Figure 5. Seismic data used for the interpretation of faults below the upper Miocene to lower Pliocene unconformity in the area of the northern high. A) Time slice at 3160 ms. B) Coherency at Time slice at 3160 ms. C) Spectral decomposition 0-250 ms below UMLPU at 13 Hz. D) Interpretation of faults below the upper Miocene to lower Pliocene unconformity. For location of time slice and attributes, see Figure 4.

Figure 6. Schematic map showing the oblique subduction of the Caribbean Plate and the occurrence of a dextral strike-slip deformation zone at the rear of the South Caribbean Deformed Belt. Note the formation of sigmoidal faults within the dextral shear zone, and the corresponding clockwise vertical-axis block rotation (modified from Galindo and Lonergan, 2013)

Figure 1. Mechanism to generate sigmoidal-Z normal faults within a dextral shear zone. A) Structures formed in a simple-dextral shear zone; faults and folds form at 45° to the boundaries of the zone. Note the change in the strike of the structures in transpressional or transtensional settings. B) Incremental strain at $\Psi=30^\circ$. C) Incremental strain at $\Psi=45^\circ$. D) Incremental strain at $\Psi=60^\circ$. E) Sigmoidal normal faults as a result of the incremental strain within a simple-dextral shear zone.

224x95mm (300 x 300 DPI)

Figure 2. A) Location of the study area in the NW corner of South America. The Bahia Basin is in front of the NW corner of the Santa Marta Massif, at the end of two regional strike-slip fault systems: the EW trending Oca Fault System (OFS), and the NW-SE trending Santa Marta-Bucaramanga Fault (SMBFS). Faults A, B, C and D are the main faults observed in the Bahia Basin.

184x127mm (300 x 300 DPI)

B) NW-SE cross section showing the South Caribbean Deformed Belt and the Bahia Basin towards the rear of the accretionary prism (modified from Galindo and Lonergan, 2020).

279x170mm (300 x 300 DPI)

Figure 3. A) Upper Miocene to lower Pliocene unconformity time-structure map. The NE-SW trending Bahia Fault compartmentalizes the basin and separates the high blocks in the NW (SH=Southern High, CH=Central High, NH=Northern High) from the main depocenter in the SE. The blue box highlights the location of the focus area in the northern high. The contour interval is 100 ms TWT. B) Upper Miocene to lower Pliocene unconformity structure map. Faults A, C and D form the boundaries to the Bahia Basin. Bahia Fault is formed by three main segments (Bs=Bahia south, Bc=Bahia central, Bn=Bahia north). Note the North position towards the upper right corner (modified from Galindo and Lonergan, 2020)

130x167mm (300 x 300 DPI)

Figure 4. Uninterpreted (above) and interpreted (below) S-N seismic section across the northern high of the Bahia basin showing the closely spaced, low-displacement, extensional faults. Colored horizons correspond to main unconformities interpreted within the basin: in green, UMLPU (Upper Miocene to Lower Pliocene Unconformity); in blue, MMU (Middle Miocene Unconformity); in magenta, UOLMU (Upper Miocene to Lower Miocene Unconformity); in orange, MEU (Middle Eocene Unconformity).

207x181mm (300 x 300 DPI)

Figure 5. Seismic data used for the interpretation of faults below the upper Miocene to lower Pliocene unconformity in the area of the northern high. A) Time slice at 3160 ms. B) Coherency at Time slice at 3160 ms. C) Spectral decomposition 0-250 ms below UMLPU at 13 Hz. D) Interpretation of faults below the upper Miocene to lower Pliocene unconformity. For location of time slice and attributes, see Figure 4.

160x212mm (300 x 300 DPI)

Figure 6. Schematic map showing the oblique subduction of the Caribbean Plate and the occurrence of a dextral strike-slip deformation zone at the rear of the South Caribbean Deformed Belt. Note the formation of sigmoidal faults within the dextral shear zone, and the corresponding clockwise vertical-axis block rotation (modified from Galindo and Lonergan, 2013)

70x60mm (300 x 300 DPI)