Evolution of the Bahia Basin: Evidence for Vertical-Axis Block Rotation and Basin Inversion at the Caribbean Plate Margin Offshore Northern Colombia*

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Abstract

The Bahia Basin is located in the NW corner of South America where a complex history of subduction, accretion and transpression has been on going since Cretaceous times. The Bahia Basin lies just offshore from major strike-slip fault systems that affect northern Colombia and some 60 km behind the front of the modern accretionary wedge, where the Caribbean Plate is being subducted obliquely beneath South America. This study uses a high quality 3D PSTM seismic volume to document the structural styles associated with the evolution of the Bahia Basin since the Miocene. A complex array of structures forming in a transtensional-transpressional setting have been found and it appears that the Bahia Basin initially formed as a right-lateral transtensional basin, with vertical axis rotation of blocks located on the uplifted north-western margin of the basin. Subsequently in Pliocene times, it has been subjected to inversion. We propose that the Bahia Basin, and related smaller depocentres immediately NW of the main basin, formed in a zone of distributed strike-slip deformation at the rear of the Miocene-Recent accretionary wedge. An understanding of how the Neogene basins located along the margin between the Caribbean and South American plates have formed and evolved is required for successful hydrocarbon exploration in the deep-water basins in this structurally complex area.

Introduction

The southern margin of the Caribbean Plate in the NW corner of South America is one of the major hydrocarbon provinces in the world, with a daily production of oil and gas greater than four MMBO a day (Escalona and Mann, 2011). This is the result of decades of active exploration during which a large amount of geological data (e.g. seismic, wells) have been acquired and interpreted. These data have contributed to a number of different hypotheses to describe the evolution of the Caribbean and NW South America. Models to explain the tectonic evolution of this area of complex plate interaction range from an in-situ origin of the Caribbean Plate (e.g. Frisch et al., 1992; Meschede and Frisch, 1998; James, 2009a, 2009b) to a variety of models supporting a migration of the Caribbean Plate from the Pacific (e.g. Burke, 1988; Pindell et al., 1988; Mann, 1999; Higgs, 2009; Pindell and Kennan, 2009; Escalona and Mann, 2011). However, most authors agree on an eastern movement of the Caribbean relative to the Americas since Miocene times (van Benthem et al., 2013) and the age and location of accretionary prisms in the

South Caribbean Deformation Belt (SCDB – Figure 1, e.g. Duque-Caro, 1979; Ruiz et al., 2000; Corredor et al., 2003; Flinch, 2003; Kroehler et al., 2011) and Lesser Antilles (e.g. Torrini and Speed, 1989) would support this model.

The aim of this presentation is to test and evaluate the presence of strike-slip deformation in the offshore Bahia Basin because of the continuous oblique subduction of the Caribbean Plate beneath South America since Miocene times. The Bahia Basin (blue box, Figure 1) is located in the NW corner of the South American Plate, at the rear of the South Caribbean Deformation Belt (SCDB), and close to the termination of onshore, major, regional strike-slip faults and structural blocks. How the onshore structures relate to the offshore structure is as yet not well understood. This study describes the evolution of the Bahia Basin since Miocene times based on the interpretation of high-quality 3D seismic data. We propose that the Bahia Basin formed in a strike-slip setting consistent with its location at the rear of an accretionary system forming due to oblique subduction. We document vertical axis block rotations and transpressional structures that formed within a zone of complex strike-slip deformation.

Geological Setting

The area of study is located in the Bahia Basin (Duarte et al., 2006) at approximately 11°20' latitude N and 74°33' longitude W, in front of the city of Santa Marta, on the Colombian Caribbean coast. This area is surrounded by different structural blocks whose interaction resulted in the current configuration of NW South America and Caribbean plates. These structural blocks are Sinu and San Jacinto Fold Belts, Plato-San Jorge Basin and Santa Marta Massif. These blocks are bounded by major fault systems with complex geological histories. The main fault zones in this area are the frontal thrust of the accretionary prism known as the South Caribbean Deformation Front, the Romeral Fault Zone, the Santa Marta-Bucaramanga Fault and the Oca Fault (Figure 1).

The Sinu and San Jacinto Fold Belts are part of the accretionary wedge that developed due to the double-staged collision of Caribbean and South American Plates (Figure 1A). The San Jacinto Fold Belt (SJFB) is the innermost of the accretionary wedges (Flinch et al., 2003) which resulted from dextral-transpressional collision/accretion between the Caribbean and South American Plates (Cediel et al., 2003; Kennan and Pindell, 2009; Pindell and Kennan, 2009) during Late Cretaceous to Eocene (Ruiz et al., 2000) or Paleocene to Oligocene (Flinch, 2003) times. The SJFB is composed of west-vergent imbricated thrusts involving the oceanic crust and a sedimentary sequence of Late Cretaceous to Miocene age. The SJFB is bounded to the east by the Romeral Fault Zone, which is considered the main boundary between the South American continental crust and the oceanic crust of the Caribbean Plate.

The Sinu Fold Belt (also called the "Outer Accretionary Wedge" by Flinch et al., 2003; Figure 1A) corresponds to a second accretionary stage, related to Andean Orogeny, which occurred during Late Miocene to Recent times (e.g. Duque-Caro, 1979; Ruiz et al., 2000). It is composed of west-vergent imbricate thrusts forming tight anticlines with the development of typical piggyback basins, which are filled with a thick sequence of Plio-Pleistocene syntectonic sediments (e.g. Ruiz et al., 2000; Corredor et al., 2003). The main detachment is located on a sequence of Upper Oligocene-Lower Miocene over-pressured shales, which are also the source of the extensive mud diapirism observed along the Colombian coast (e.g. Duque-Caro, 1979; Vernette et al., 1992; Ruiz et al., 2000).

The Plato-San Jorge Basin lies to the south of the study area between the Romeral Fault to the west and the Santa Marta-Bucaramanga Fault to the east (Figure 1). This basin is filled by a thick, 2-8 km, sequence of paralic and marine sediments of late Eocene to Recent age, and is compartmentalized by deep-rooted normal faults that affect the basement and sediments as young as late Miocene in age (Duque-Caro, 1979; Cediel et al., 2003; Flinch, 2003; Montes et al., 2010). Inversion structures due to the reactivation of these faults during the Andean Orogeny have been observed close to the boundaries of the basin, especially associated with the Romeral Fault Zone, exposing strata as old as Miocene (Flinch, 2003; Montes et al., 2010).

The Santa Marta Massif (SMM) is bounded on the west by the transpressional left-lateral Santa Marta - Bucaramanga Fault and the right-lateral Oca Fault to the north (Figure 1), and it forms the highest coastal relief in the world (5800 m above sea level, Cardona and Ojeda, 2010). The most recent models for the formation of the SMM suggest that it has rotated clockwise by 30° in response to a simultaneous shortening in the Perijá Range and the opening of the Plato-San Jorge Basin since the Late Eocene, giving a right-lateral displacement of 100 km on the Oca Fault and 45 km of left-lateral displacement on the Santa Marta-Bucaramanga Fault (Montes et al., 2010; Bayona et al., 2011, 2012; Ayala et al., 2012). The rotations have been documented from palaeomagnetic studies (Montes et al., 2010). High rates of uplift of the Santa Marta Massif occurred during Oligocene to Early Miocene times, and again from the Middle Miocene to the present day (Villagómez et al., 2011). The Oca and Santa Marta – Bucaramanga faults have continued to be active to the present day (Audemard, 1996; Idárraga-García and Romero, 2010; Chicangana et al., 2011).

The Bahia Basin is located just offshore of the Santa Marta-Bucaramanga and Oca faults (Figure 1). Very few published studies discuss the basin. Duarte et al. (2006) presented a chrono-stratigraphic scheme for the northern Colombian-Caribbean basins (between the Magdalena Fan and the Guajira Peninsula), which included the Bahia Basin and they showed it to be the thickest in the area. They also noted that it was affected by both extension and contraction that they attributed to a continuation of the Romeral Fault Zone. Hernández and Guerrero (2006) briefly describe the possible continuation of the Santa Marta-Bucaramanga Fault and the Romeral Fault into the Bahia Basin, suggesting a transpressive setting where oceanic and continental crusts collide, and proposing the development of different depocenters since the Eocene.

In summary, the Bahia Basin is located in the NW corner of the South American Plate, within the South Caribbean Deformation Belt (Figure 1B), and at the termination of major, regional, strike-slip faults which bound structural blocks with different characteristics. This is a unique location in which to observe and understand the complex evolution of transpressional structures in a geological setting of oblique subduction between the Caribbean and South American Plates.

Seismic Interpretation

A high-quality, pre-stack, time migrated (PSTM) seismic volume covering an approximate area of 1,500 km² was used for this study. It consists of 1,196 lines (SW-NE) at a spacing of 25 m, and 4,056 traces (SE-NW) at a spacing of 12.5 m. In depth (Z axis), the volume has a record length of 7 seconds TWT (c. 8 km), with a sample rate of 4 ms. The seismic volume has an average frequency content of 30 Hz which gives a maximum horizontal resolution of ca. 25 m and a vertical resolution of ca. 20 m. Biostratigraphic data from one well within the seismic volume has allowed us to assign Upper Oligocene to Recent ages to the stratigraphy. However, as the well is located on the NW flank of the Bahia Basin, the ages of the deeper strata within the Bahia Basin are not constrained.

Within the seismic dataset we have mapped a deep, narrow, triangular-shaped, young basin trending SW-NE, within which ca. 4 s TWT (ca. 4.6 km) of Neogene sediments were deposited. A major fault, the Bahia Fault, forms the NW margin of the basin, and the northeastern end of the basin is bounded by a young N-S trending fold, which may be related to deformation associated with the Santa Marta-Bucaramanga Fault. The SW-NE trending Bahia Fault is composed of three main segments (X, Y, and Z; Figure 2). The footwall of this fault is marked by a prominent unconformity, which well data indicate is Late Miocene in age. We have mapped a surface of approximately similar age on the downthrown side of the Bahia Fault within the adjacent basin. This Upper Miocene unconformity is illustrated as the time-structure map on Figure 2. The offset on the Upper Miocene event shows that the Bahia Fault formed as a fault with significant extensional movement, and its footwall remains structurally higher than the adjacent basin. In addition, the shape of the Bahia Basin, where the depocentres shallow and step towards the SW, suggest that the basin formed due to right-lateral transtension (Figure 2).

To understand the geological evolution between pre- and post- Upper Miocene times, structures below and above the unconformity were mapped, and are summarized in Figure 3.

Evidence for Vertical-Axis Block Rotation

Beneath the Upper Miocene, unconformity the footwall of the Bahia Fault is deformed by a large number of closely spaced, low-displacement, extensional faults (Figure 3A). Surprisingly, the mapped traces of the faults within the footwall vary significantly in trend along the length of the fault. These faults form three groups within blocks that broadly correspond to the three fault segments that form the Bahia Fault (X, Y, and Z in Figure 2). The boundary of each block is also marked by the presence of relay zones between each fault segment and small mud diapirs are found at boundaries of the central block. In the most southerly fault block, the main set of normal faults strikes NW-SE, orthogonal to the Bahia Fault. At the western end of the block, there is a small group of NE-SW trending faults and there is a hint that fault orientations fan within the block. In the central block the faults strike between NNE-SSW and N-S. In the northern fault block, the faults form two sets separated by a normal fault that is sub-parallel to the main Bahia Fault. The faults in both sets are mainly oriented E-W, and they have sigmoidal geometries at the fault tips indicating that they formed in a zone undergoing right-lateral shear (Figure 3A).

Seismic sections through each fault set, which are oriented orthogonal to the fault traces (i.e. 'dip' sections), illustrate the similarity of faulting style within each block (Figure 4). The seismic character and seismic facies of the Miocene strata deformed by the faults is very similar and there is no reason to believe that the age of the strata within each fault block varies significantly. From these observations it appears that the footwall of the Bahia Fault is formed of three fault blocks which have a similar stratigraphy and extensional or transtensional faulting style, but that there is an unusual and unexpected change of trend of the small-scale faulting with the footwall fault blocks.

The change in trend of the normal faults between the southern and the central blocks is about 45°, whilst the change between the central and the northern one is up to 90°. There are at least two possible explanations for this observation. Firstly, there were different extensional directions in the same area at the same time prior to the Upper Miocene. However, the lack of overprinting of the fault trends would seem to preclude this hypothesis. Secondly, the blocks have undergone rotation either during the formation of the normal faults, or after the faults formed due to strike-slip deformation. We currently prefer the second hypothesis and our preliminary analysis suggests that the Bahia Fault acted as the

margin of a right-lateral shear zone. The rocks within the shear zone were subjected to transtension and formed small normal faults. As the shear zone continued to move and segments linked, the central block was rotated clockwise by ca. 45° due to the opening of a small graben along the relay zone between the southern and central segments of the Bahia Fault (Figure 2 and Figure 3A). The angle that the faults in the northern block make with the Bahia Fault and their sigmoidal plan view geometry is consistent with right-lateral movement along the Bahia Fault. Mud diapirs appear to have exploited the gaps at the edges of the rotated blocks.

Evidence for Basin Inversion

Above the Upper Miocene unconformity the main structures that dominate the area are: (1) the Bahia Fault, which has been inverted post the Late Miocene, (2) a series of NW-SE trending normal faults within the Bahia Basin itself, and (3) N-S trending anticlines, synclines and thrusts in the east of the area. This last set of structures may be related to the northern termination of the Santa Marta - Bucaramanga Fault and the continued uplift of the Santa Marta Massif (Figure 2 and Figure 3B).

Figure 5 documents the style of the inversion along the Bahia Fault. In the southernmost segment, segment X (Figure 2 and Figure 5 panel a), the geometry of the anticline and the related growth strata show a south-eastern vergence of the inversion fold and the footwall of the initial normal fault has become the hangingwall of the inverted structure. On the other hand, in the central segment (Y), the inversion is expressed as an anticline within the Bahia Basin sediments and the Bahia Fault has acted as a buttress against which the sediments of the Bahia were shortened (Figure 2 and Figure 5 panel c).

At the same time as inversion was occurring on the Bahia Fault, coeval NW-SE normal faults were forming within the Pliocene-Recent Bahia Basin sediments. This simultaneous compression and extension is typical of a strike-slip setting and the orientation of the normal faults suggests that the Bahia Basin was subjected to right-lateral transpression in Pliocene times.

Discussion and Conclusions

The structure maps below and above the Upper Miocene unconformity illustrate a change from an extensional/transtensional regime before the Late Miocene to a mainly transpressional regime after the Late Miocene. The initial regional extension might be explained as forming because of transtension where the Bahia Fault formed the main boundary of a right-lateral shear zone, which included some vertical-axis block rotation to the NW of the fault. The Bahia Basin subsequently opened as a right-lateral transtensional basin. A change to transpressional deformation is observed during Pliocene times, with inversion structures forming on the Bahia Fault. Some of the other normal faults to the NW of the Bahia Fault are also inverted at this time (Figure 3B). Shortening, possibly related to uplift of the Santa Marta Massif, is observed along the eastern margin of the Bahia Basin.

This deformation was occurring in the context of oblique subduction along the SCDB since Miocene times. Seismic line B in Figure 1 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. 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; amongst many others) 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 (~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 blocks in the footwall of the Bahia Fault (Figure 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 (e.g. van der Hilst and Mann, 1994; Miller et al., 2009; Bezada et al., 2010; van Benthem et al., 2013), GPS measurements (e.g. Weber et al., 2001; Trenkamp et al., 2002), seismology (e.g. Corredor, 2003; Cortés and Angelier, 2005), structural restorations (e.g. Corredor et al., 2003), field studies (e.g. Lara et al., 2013) and tectonic plate restorations (e.g. Müller et al., 1999) 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 SCDB curves to the east in comparison to the Sinu Fold belt to the south of the Magdalena Fan where the accretionary prism forms a higher angle with the Caribbean Plate. Right lateral displacement has occurred on the Oca Fault since Late Eocene times also testifying the significant strike-slip deformation behind the zone of subduction and accretion during the Miocene.

Clockwise vertical axes block rotations have also been documented onshore in Colombia and Venezuela from several paleomagnetic studies (summarized by Montes et al., 2010 and Audemard, 2009, respectively) as a result of the complex interaction of multiple tectonic blocks during the evolution of the NW corner of South America. 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.

In conclusion, we have identified a new fault, named the Bahia Fault, located offshore northern Colombia along the boundary zone between the Caribbean and South American plates. It occurs within a zone of distributed strike-slip deformation at the rear of the Miocene-Recent SCDB accretionary wedge and has been the locus of right-lateral transtension leading to clockwise rotation of blocks within its hangingwall and the opening of the deep Bahia Basin in Miocene to early Pliocene times. Subsequently in the Pliocene, the fault underwent right-lateral inversion. Future work will focus on the kinematic analysis of each stage of the evolution (i.e. transtension and transpression) of the Bahia Basin and its relation to the evolution of the NW corner of South America.

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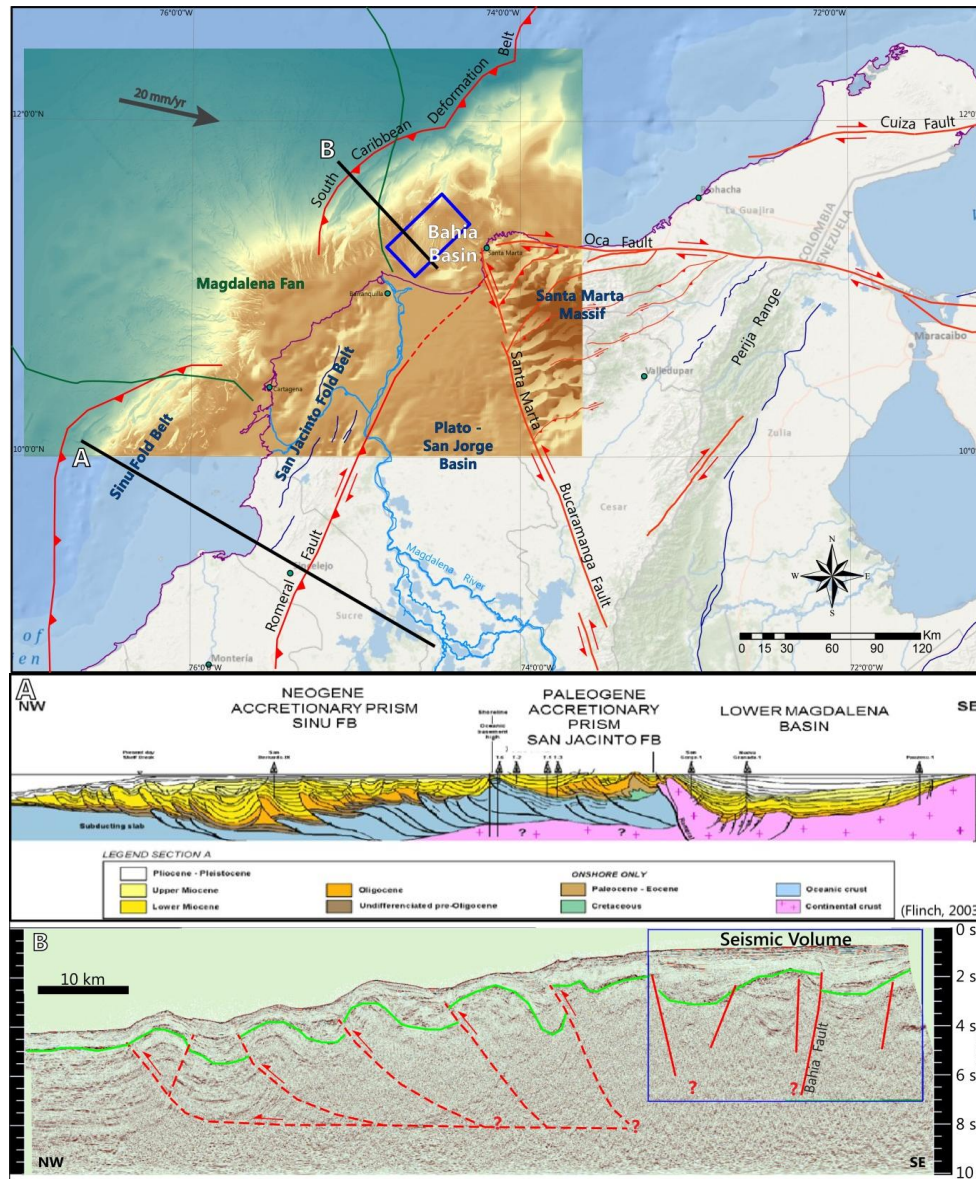
Figure 1. Summary of the main structural elements in the NW corner of South America and location of the Bahia Basin. Cross section A shows Sinu and San Jacinto accretionary prisms (Flinch, 2003). Cross section B shows the location of the Bahia Basin behind the SCDB; the Upper Miocene unconformity is shown in green. The blue box shows the location of the 3D seismic volume used in this study. Grey arrow is the current motion vector of the Caribbean Plate (Trenkamp et al., 2002)
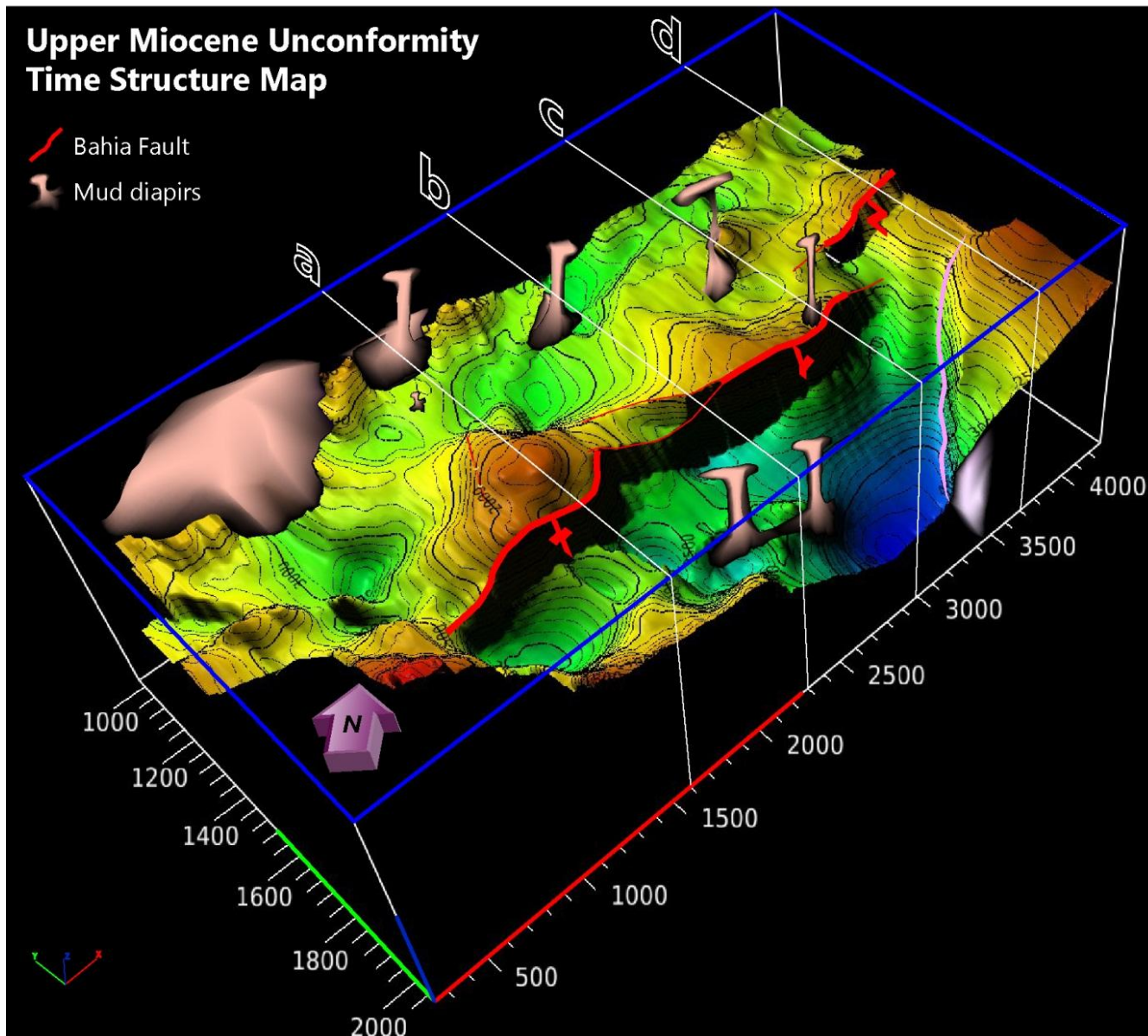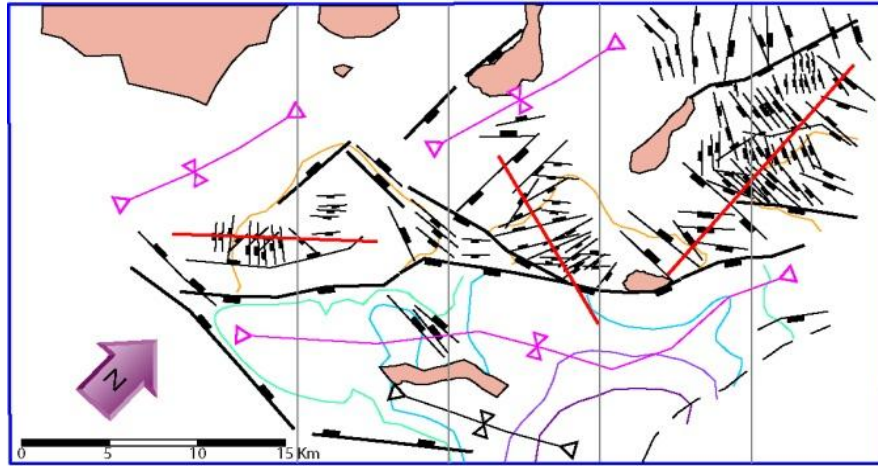
Figure 2. Time structure map of the Upper Miocene Unconformity. The Bahia Fault (in red) is formed of at least three segments (X, Y, Z) associated with three high areas in the footwall of the fault. The white lines are the location of the seismic panels in Figure 5.
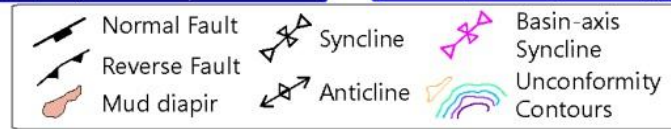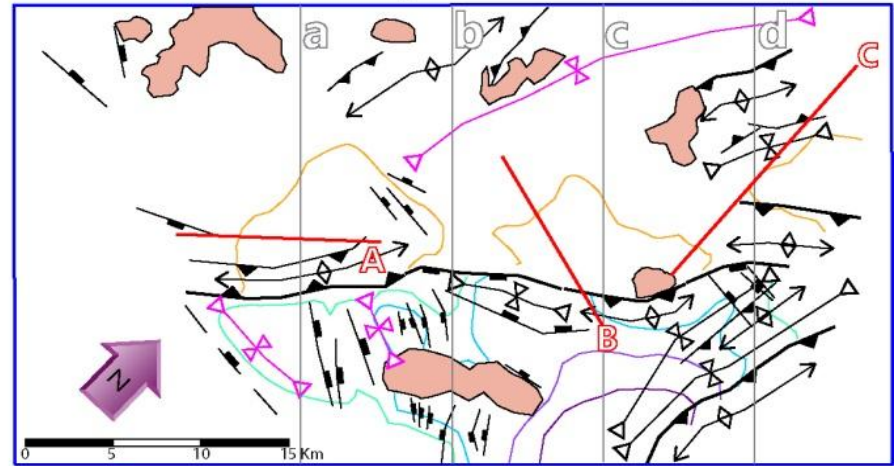
Figure 3. Summary of the structures mapped bellow and above the Upper Miocene Unconformity. Contours on unconformity surface in Bahia Basin and on footwall of Bahia Fault are shown for reference; blue-purple are deep; yellow is shallow. Red lines show the location of the seismic panels in Figure 4. Grey lines show the location of the seismic panels in Figure 5.
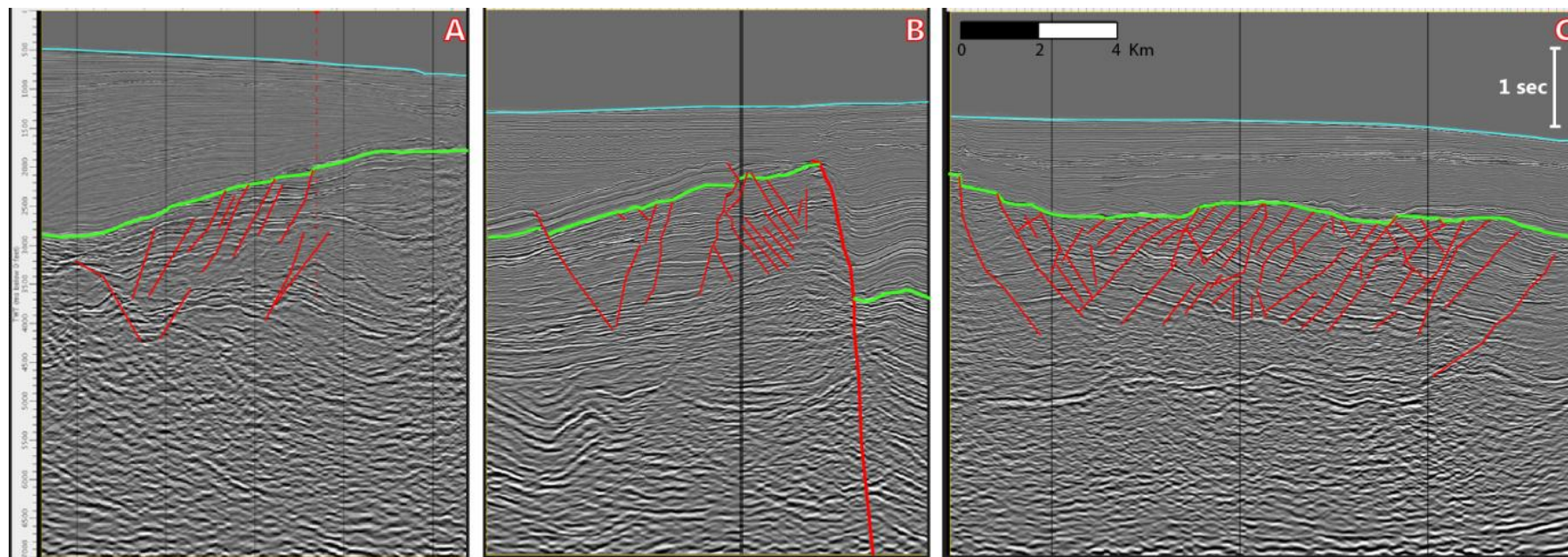
Figure 4. Seismic panels oriented approximately at right angles to the trend of the normal faults observed in the footwall of the Bahia Fault; green event is the Upper Miocene unconformity (See Figure 3 for location).
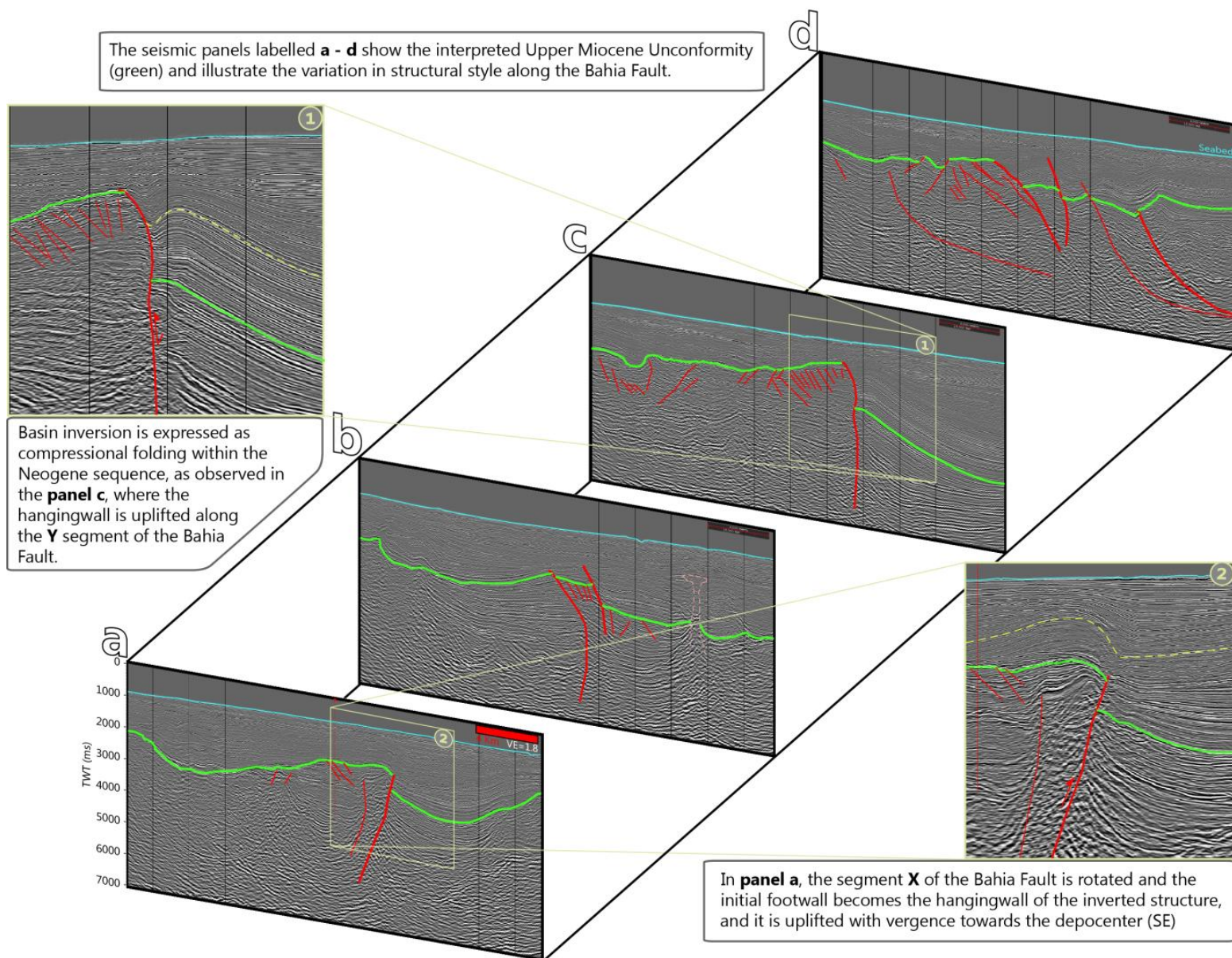
The seismic panels labelled **a - d** show the interpreted Upper Miocene Unconformity (green) and illustrate the variation in structural style along the Bahia Fault.

Basin inversion is expressed as compressional folding within the Neogene sequence, as observed in the **panel c**, where the hangingwall is uplifted along the **Y** segment of the Bahia Fault.

In **panel a**, the segment **X** of the Bahia Fault is rotated and the initial footwall becomes the hangingwall of the inverted structure, and it is uplifted with vergence towards the depocenter (SE)

Figure 5. Seismic panels a, b, c, d (see Figure 2 and Figure 3 for location) show the interpreted Upper Miocene unconformity (in green) and illustrate the variation in structural style along the Bahia Fault. Boxes labeled 1 and 2 show details of the inversion structures along the trend of the Bahia Fault.
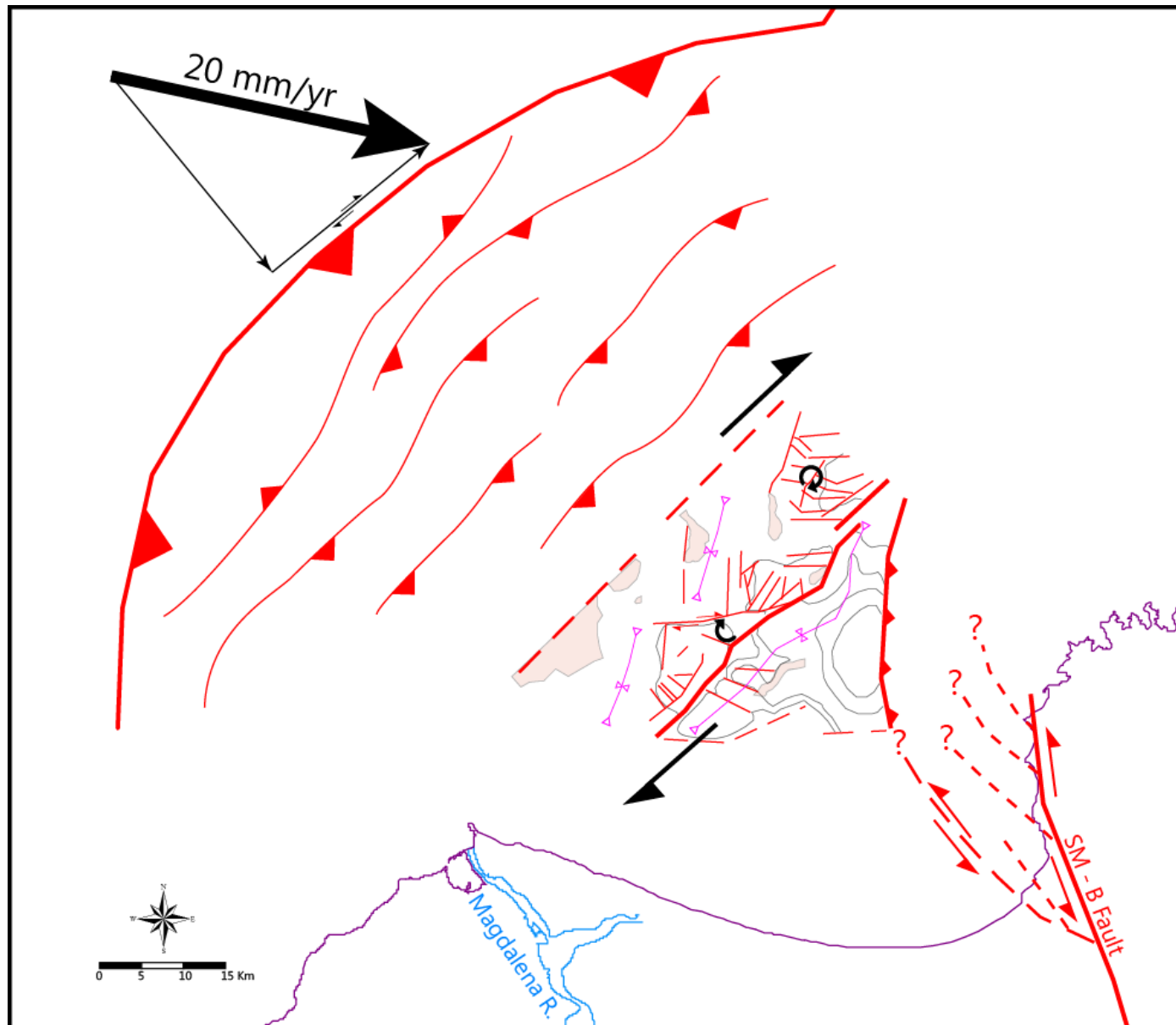
Figure 6. Schematic map showing the oblique subduction of the Caribbean Plate and the occurrence of a dextral strike-slip deformation zone (including vertical-axis block rotations) at the rear of the SCDB. In the east of the area of study, compressional folding may be related to the northern termination of the Santa Marta – Bucaramanga Fault. The thrusts of the accretionary prism are interpreted using bathymetry data.