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This work integrates stress data from Global Positioning System measurements and earthquake focal mechanism solutions, with new borehole breakout and natural fracture system data to better understand the complex interactions between the major tectonic plates in northwestern South America and to examine how the stress regime in the Eastern Cordillera and the Llanos foothills in Colombia has evolved through time. The dataset was used to generate an integrated stress map of the northern Andes and to propose a model for stress evolution in the Eastern Cordillera. In the Cordillera, the primary present-day maximum principal stress direction is WNW–ESE to NW–SE, and is in the direction of maximum shortening in the mountain range. There is also a secondary maximum principal stress direction that is E–W to ENE–WSW, which is associated with the northeastward "escape" of the North Andean block, relative to stable South America. In the Cupiagua hydrocarbon field, located in the Llanos foothills, the dominant NNE–SSW fractures are produced by the Panama arc–North Andes collision and range-normal compression. However, less well developed asymmetrical fractures oriented E–W to WSW–ENE and NNW–SSE are also present, and may be related to pre-folding stresses in the foreland basin of the Central Cordillera or to present-day shear associated with the northeastward "escape" of the north Andean block. Our study results suggest that an important driver for orogenic deformation and changes in the stress field at obliquely convergent subduction zone boundaries is the arrival of thickened crust, such as island arcs and aseismic ridges, at the trench.

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1. Introduction

Present-day stress in the northern Andes (Fig. 1) is a result of the convergence of the South American, Caribbean, and Nazca plates and the Panama microplate. Global Positioning System (GPS) measurements (Trenkamp et al., 2002) show that the North Andean block is escaping toward the northeast relative to the stable South American plate along a transpressive system of faults located along the Merida Andes, Eastern Cordillera, and Ecuadorian Andes (Fig. 2). Simultaneously, in the Eastern Cordillera of Colombia, the on-going Panama Arc–South America collision is driving NW–SE permanent shortening and rapid uplift of the range. Low-angle subduction of the buoyant Caribbean plate is also driving permanent NW–SE shortening in the Merida Andes and Eastern Cordillera. Knowledge of the evolving stress regime in the Eastern Cordillera is key to understanding the geodynamic processes at work within the region, as well as the evolution of structural traps and fracture systems for hydrocarbons. The present-day geology shows the cumulative results of all the deformational events that have affected the region. To better understand both the neostress and paleostress regimes in the Eastern Cordillera, we have analyzed data from a variety of stress indicators. The present-day stress regime can be inferred from stress-induced borehole breakouts, as well as GPS vectors, and earthquake focal mechanism solutions. The paleostress is inferred from natural fracture systems and the orientation of structural features in the Llanos foothills. It can also be inferred from geologically dated measurements of north Andean northeastward "escape", the timing of the Panama arc collision, and age data for the uplift of the Eastern Cordillera. This study suggests that the range-normal compressive stress field responsible for deforming rocks and producing the structural traps and fracture systems in the Eastern Cordillera in the last 12 Ma has evolved to include a range-parallel shear component in the last 2 Ma.

Paleostress analysis is an important tool in oil and gas exploration, development, and reservoir simulation, constraining the development of subsurface fracture systems models. Subsurface
fracture systems in hydrocarbon reservoirs usually result from paleostress that is unrelated to the present-day stress (Engelder, 1987). However, the neostress regime can strongly impact the permeability of fractures that formed in a different, older stress regime. It is important therefore to understand how the stress regime has evolved through time.

The North Andean margin provides an excellent Present-day example of an evolving stress field associated with oblique convergence and arc collision at a subduction zone. The strain associated with oblique convergence at subduction zones is often partitioned between trench-normal contraction on thrust faults and trench-parallel strain on strike-slip faults (Fitch, 1972; Jarred, 1986; McCaffrey, 1994). In general, fore arc slivers form over the region of interplate coupling and are driven along strike by the basal shear (Platt, 1993; McCaffrey et al., 2000). A volcanic arc can help the partitioning process by localizing the margin-parallel shear strain to the back arc. In this study we plate boundary, inverted the back arc basin, and displaced the present collision with the Panama arc has increased coupling on the plate boundary zones, and intraplate deformation. The main results from the study can be summarized as follows. In northern Colombia the Caribbean plate is converging with stable South America in an E−SE direction at a rate of 20 ± 2 mm/a (Fig. 2). Panama is actively colliding with northwestern South America at a rate of approximately 25 mm/a. The large eastward components of the GPS vectors in northern Colombia (Fig. 1, CART, MONT, RION, MZAL) suggest transfer of motion from the Panama microplate. The oceanic Nazca plate and the aseismic Carnegie Ridge are rapidly subducting at the Ecuador−Colombia trench at a rate of 58 ± 2 mm/a relative to stable South America. Approximately 50% of the Nazca−South America convergence is locked at the subduction interface, producing elastic deformation in the overriding South American plate. GPS measurements show that the northern Andes is escaping northeastward at a rate of 6 ± 2 mm/a relative to stable South America (Fig. 1, e.g., BOGO, PASTO, BUCM, MERI, VDUP, MZAL).

### 2. Present-day stress field data

#### 2.1. Global Positioning System

GPS studies are an important method for studying the kinematics of plate boundary zones, and intraplate deformation. The velocity vectors used for this study (Fig. 1) are from the Central and South American (CASA) GPS project (Trenkamp et al., 2002) which measured plate motions and crustal deformation of the four major plates in the region. The main results from the study can be summarized as follows. In northern Colombia the Caribbean plate is converging with stable South America in an E−SE direction at a rate of 20 ± 2 mm/a (Fig. 2). Panama is actively colliding with northwestern South America at a rate of approximately 25 mm/a. The large eastward components of the GPS vectors in northern Colombia (Fig. 1, CART, MONT, RION, MZAL) suggest transfer of motion from the Panama microplate. The oceanic Nazca plate and the aseismic Carnegie Ridge are rapidly subducting at the Ecuador−Colombia trench at a rate of 58 ± 2 mm/a relative to stable South America. Approximately 50% of the Nazca−South America convergence is locked at the subduction interface, producing elastic deformation in the overriding South American plate. GPS measurements show that the northern Andes is escaping northeastward at a rate of 6 ± 2 mm/a relative to stable South America (Fig. 1, e.g., BOGO, PASTO, BUCM, MERI, VDUP, MZAL).

### 2.2. Borehole breakouts

Borehole breakouts indicate the horizontal stress field at intermediate depths; usually less than 5 km. Borehole breakouts are consistently oriented elongations in the wellbore cross-section that form as a result of differential stress applied to an initially circular borehole. Borehole breakouts were first observed by Cox (1970) in the Wapiabi shales of west-central Alberta. However, it was not until later in the early 1980s that they were attributed to the in-situ stress field (Gough and Bell, 1981; Hickman et al., 1982; Plumb, 1982; Cox, 1983). A borehole breakout occurs when the stresses around the borehole exceed that required to cause compressive failure of the borehole wall (Zoback et al., 1985). The development of intersecting conjugate shear planes causes spalling of the borehole wall, resulting in the enlargement of the well bore. In a vertical borehole, the wall shear stress is greatest in the direction of the minimum horizontal stress (Sh). The long axes of borehole breakouts therefore, are oriented approximately perpendicular to the maximum horizontal stress direction (Shmax) (Plumb and Hickman, 1985).

The borehole breakout data presented in this work (Fig. 1) is from four-arm caliper, high resolution dipmeter logs, and was collected from 60 industry wells in the Eastern Cordillera and surrounding areas. Each well was assigned a quality ranking based on standard deviation, number of breakouts, and cumulative length of broken out intervals using the rating scheme of Zoback and Zoback (1989). The breakout symbols plotted on the map represent the location and direction of Shmax of each of the wells. The bars show the direction of the mean azimuth of Shmax and the length of the bars corresponds to the quality ranking of the breakout data which range from A to D. A “A” rating represents a well with many breakouts which have tightly clustered elongation azimuths. A “D” ranking represents a well with very few breakouts, multiple azimuthal populations, and/or a large standard deviation for the mean azimuth. In general, borehole breakout orientations are bimodal, in the sense that data between 180° and 360° are equivalent to those between 0° and 180°. Borehole breakouts in the region show significant scatter, but we propose that the data fall into three major subsets by region: northern, central, and southern. The northern subset is made up of wells located above 6° N. Though a number of these wells show variable Shmax orientation, the majority have E−W trending Shmax. The central subset is made up of wells located between 2° N and 6° N. Most of the wells in this subset have NWN−ESE trending Shmax. Wells in the southern segment (0°−2° N) have a NW−SE and less commonly NNE−SSW trending Shmax. It is important to point out that there are no clear patterns of azimuthal variations with depth in the individual wells or in the data subsets except for wells in the Llanos basin where the data shows a change in breakout orientation at about 7800 ft (Torres Fleischmann, 1992). Below this depth, there are two main breakout population clusters. These correspond to Shmax orientations of 110° and 070°.

#### 2.3. Earthquake focal mechanism solutions

Some of the stress data in Fig. 1 are derived from single earthquake focal mechanism solutions (FMS) from the World Stress Map database (Reinecker et al., 2005). An earthquake focal mechanism solution is constructed using the radiation pattern of seismic waves generated by an earthquake. The solution contains two perpendicular planes that represent the fault plane and the auxiliary plane, and divide the volume into compressional and extensional quadrants. The orientation of the compressional (P), intermediate (B), and extensional (T) axes are determined by the orientations of these planes. It is important to point out, that the moment tensor axes of earthquake focal mechanisms are not equal to the principal stress axes. The only conclusion that can be made is that the maximum principal stress lies within the dilatational quadrant of the focal mechanism (McKenzie, 1969). The principal strain axes of earthquake focal mechanism solutions (P-axis, B-axis, and T-axis) are used as proxies for the orientation of the principal stresses axes σ1, σ2, and σ3. To account for the uncertainties in this first-order approximation, the quality of the
stress orientations derived from FMS in the World Stress Map database is limited to a C-quality regardless of the size of the earthquake and how well the focal mechanism is constrained. This quality ranking assumes a deviation of up to \( \pm 25^\circ \). Focal mechanism solutions located in the vicinity of a plate boundary and with kinematics similar to the plate boundary, are omitted and flagged as possible Plate Boundary Events (PBE) indicating that the \( P-, B-, \) and \( T-\) axes of the focal mechanism solutions might predominantly reflect the geometry and kinematics of the plate boundary, rather than the orientation of the regional stress field. The accuracy of stress derivations from the FMS presented in this work are limited by the fault-plane ambiguity and the coefficient of friction (Barth et al., 2008).

\( SH_{max} \) orientations determined from FMS shown in Fig. 1 appear to fall into two main subsets: showing NW–SE and ENE–WSW maximum compressive stress directions (Ego et al., 1996; Corredor, 2003; Cortés and Angelier, 2005). The NW–SE compression has been associated with Caribbean–South American convergence and Panama–South America collision (Kellogg and Vega, 1995; Taboada et al., 2000; Trenkamp et al., 2002; Corredor, 2003; Colmenares and Zoback, 2003; Acosta et al., 2004), and the ENE–WSW compression has been ascribed to Nazca–South America convergence and Carnegie Ridge subduction at the Colombia–Ecuador trench (Ego et al., 1996; Gutscher et al., 1999; Trenkamp et al., 2002; Corredor, 2003; Colmenares and Zoback, 2003; Egbue and Kellogg, 2010).

3. Paleostress field data

The paleostress field in an orogenic belt can be inferred from the geologic record, including fault and fold orientations, age-constrained fault displacements, rock deformation studies, and natural fracture orientations. Here we summarize structural models for the Eastern Cordillera and present new natural fracture data.

3.1. Structure of the Eastern Cordillera

The Eastern Cordillera has been generally interpreted as a wide Mesozoic extensional basin that evolved into a foreland basin for the Central Cordillera, and was subsequently inverted by Andean compression and orogeny (Colletta et al., 1990; Dengo and Covey, 1993; Cooper et al., 1995). Based on a retrodeformed cross-section through the Eastern Cordillera, Colletta et al. (1990) proposed that the Cordillera was formed by the inversion of two deep Upper Jurassic–Lower Cretaceous basins during Mio-Pliocene times. In this model, the structure is controlled by low angle thrusts and reactivated normal faults that constitute frontal ramps. They estimated a total shortening of at least 105 km with a decollement at a depth of about 20 km. Toro et al. (2004) obtained similar results along two partial volume-balanced transects of the Cordillera. Dengo and Covey (1993) proposed that basement-detached (“thin-skinned”) shortening was followed by uplift on
high-angle basement involved reverse faults (“thick-skinned”) deformation and estimated approximately 150 km of shortening (40%) from a regional retrodeformable cross-section. Cooper et al. (1995) proposed that deformation in the Llanos foothills was predominantly inversion of pre-existing extensional faults by basement-involved “thick skinned” listric reverse faults. They estimated only 68 km of shortening.

Egbue and Kellogg (2012) studied the three-dimensional structural evolution of the Piedemonte block in the NE–SW trending central Llanos foothills, the frontal thrust zone along the eastern flank of the Eastern Cordillera (Fig. 3). NW–SE directed compression has formed a duplex zone containing as many as five east-verging stacked thrust sheets. Using 2-D and 3-D seismic reflection data, surface geology, and well data, Egbue and Kellogg (2012) modeled approximately 4 km (9%) NW–SE shortening in the Late Oligocene (25 Ma) followed by 13–19 km (30–40%) NW–SE shortening in the last 10 million years.

Based on paleostress indicators (fault and fold orientations), Cortés et al. (2005) present evidence of ENE–WSW directed compression and shear stresses in the present day western flank and center of the Eastern Cordillera during the Maastrichtian–Late Paleocene, prior to the uplift of the Eastern Cordillera. Geologic indicators of ENE–WSW compression and right-lateral shear in the Eastern Cordillera in the last 2 Ma are largely obscured by the ongoing NW–SE compression. The timing of this northeastward “escape” is inferred from geological observations in Ecuador, southern Colombia, and Venezuela (compiled in Egbue and Kellogg, 2010). The ongoing ENE–WSW compression is also evidenced by

![Figure 3](image_url)
present-day GPS measurements, earthquake focal mechanisms, and bore-hole breakout data.

3.2. Natural fractures

Natural fractures are typically present in all rocks to varying degrees. In fold and thrust belt regions, the rocks are even more intensely fractured. These fractures are developed and/or modified during deformation in well consolidated rocks. Most of the tight, well-cemented reservoirs, like those in the flanks of the Eastern Cordillera, have natural fractures which are important features that control fluid-reservoir dynamics. Subsequent stress regimes can strongly affect the permeability of ancient fractures that formed in a different, older stress regime. The propagation paths for fractures in a geologic setting are strongly influenced by the state of stress and are only weakly dependent on the rock fabric (Olson and Pollard, 1989). Vertical fractures propagate normal to the least principal stress, thus, they follow the path of the stress field present at the time of their propagation (Engelder and Geiser, 1980). By examining a map of fracture-set orientation, we can infer the differential stress that was active during their propagation.

In the Cupiagua hydrocarbon field (Fig. 3) on the eastern flank of the Eastern Cordillera, cores and image logs (Ultrasonic Borehole Imager-UBI and Fullbore Formation MicroImager-FMI) show that natural fractures are present at different stratigraphic intervals including the main reservoirs. Fractures are a modifier of reservoirs, enhancing permeability when they occur open and connected, and reducing permeability when they are closed. In the reservoir intervals, fractures with a low acoustic amplitude and high transit time (i.e. dark on UBI images) are dominant, and are interpreted as being open or partially open at the borehole wall (Adams et al., 1999). A high transit time suggests an aperture at the borehole wall and a mud or clay fill which gives rise to low acoustic impedance. However, clay smeared fractures are rare in cores from Cupiagua; hence the fractures are interpreted as being filled with drilling mud. Fractures with high acoustic amplitude are rare. UBI images show acoustic amplitude contrast which is a response to changes in acoustic impedance at the borehole wall, which in clastic sequences is related mainly to changes in matrix porosity and lithology. Within the Cupiagua field, open fractures commonly occur in proximity to cataclastic faults suggesting that fracture propagation has a genetic relationship with major deformation episodes. The mean fracture density varies within the reservoir units, and ranges between 0.11–0.62 fractures per foot (Adams et al., 1999). A stratigraphic summary diagram for the Llanos foothills (Fig. 4) shows the key lithostratigraphic units/formations, reservoir units, unconformities, and detachment levels. In general, the Barco formation is more intensely fractured than the Mirador

![Fig. 4](image-url)
and Guadalupe Formations. It is important to point out that the variations in fracture density may not be solely a result of geological factors. It is also dependent on variations in UBI image quality.

Based on log images (UBI and FMI) from wells in the Cupiagua field, we recognize three main families of fractures in the Cupiagua field (Fig. 5). The data was classified, correlated, and plotted as rose diagrams to group fracture events into clusters/families. A fracture dip vs depth plot from UBI for the wells (Fig. 6) shows that most of the natural fractures present in the reservoir between 12,000 and 16,000 ft are steeply dipping to subvertical (40–90°) suggesting that the maximum principal stress directions are subhorizontal. Only one anomalous well shows a wide dispersion of fracture dip angles below 15,000 ft. Stearns (1967) observed that infold structures in the western United States, conjugate and tensile fractures form sets that are oriented in varying directions relative to bedding and the fold hinge line (Fig. 7). In Cupiagua, a NW–SE trending fracture set is widespread throughout the field, and is dominant in the southern portion of the field (Fig. 5). These fractures are aligned parallel to the present-day regional stress maximum. An E–W to WNW–ESE family of fractures is approximately orthogonal to the axis of the structure. This family of fractures is dominant in the northern segment of the field, but these fractures also occur in the central and southern segments. This fracture set corresponds to Stearns’ fracture type 1 (Fig. 7a). A third NNE–SSW family of

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Fig. 5. Fracture strike rose diagram plot for the northern, central, and southern Cupiagua field. The Cupiagua hydrocarbon field is located in Fig. 3. Black dots show well locations.
fractures is common in the central portion of the field (Fig. 5), and is also present in the southern segment. These type 2 fractures run parallel to the axis of the Cupiagua structure and occur in both the crest and flank regions.

4. Discussion

4.1. Present-day stress

The regional stress map (Fig. 1) shows that the primary present-day maximum principal stress direction in the Eastern Cordillera is WNW–ESE to NW–SE. This direction is roughly orthogonal to the mountain range and in the direction of maximum shortening. Colmenares and Zoback (2003) proposed that the negatively buoyant Caribbean slab may be driving the rotation of $\text{SH}_{\text{max}}$ to the ESE in the direction of relative subduction under the northern Andes. The WNW–ESE stress direction is also the Panama–North Andes relative convergence vector when corrected for the 6 mm/a northeastward “escape” of the North Andes, and the magnitude of the shortening required to build the Eastern Cordillera (68–150 km), suggests that most of the continuing shortening and uplift of the range is associated with the ongoing Panama–North Andes collision. Close to the Panama block indenter on the western side of the northern Andes, the collision-related stresses are particularly strong. For example, south of MZAL, the 1999 Armenia earthquake (Fig. 1, focal mechanism at 4.4° N, 284.3° E) may have been localized left-lateral slip on the NNE-trending Romeral fault system related to the Panama–North Andes collision (Pulido, 2003). We interpret this as Panama collision-produced shear on the broad western flank of the northeastward “escaping” North Andes block.

A secondary present-day maximum principal stress direction in the Eastern Cordillera is E–W to ENE–WSW. This is particularly pronounced in the northern termination of the Eastern Cordillera, the Bocono fault system in Venezuela, and in southern Colombia and Ecuador. We propose that this stress direction is associated with the subduction of the Carnegie Ridge and the northeastward “escape” of the North Andes relative to stable South America. The stress is particularly noticeable at the northern end of the Eastern Cordillera.

Fig. 6. Fracture dip/depth plot from UBI for Cupiagua field wells shown in Fig. 5. Different symbols represent different wells. Note that most of the natural fractures present in the reservoir between 12,000 and 16,000 ft depths are steeply dipping to subvertical (40°–90°).

Fig. 7. Schematic diagrams showing (a) fractures types associated with folding, after Stearns (1967) and (b) an example of an asymmetrical fracture unrelated to folding.
Cordillera where a left-stepping restraining bend produces permanent compressional deformation.

4.2. Paleostress

During the Late Jurassic and Cretaceous periods, the area of the present-day Eastern Cordillera was a rift basin with approximately WNW–ESE oriented extension (minimum principal stress) (Ojeda, 1996; Sarmiento-Rojas et al., 2006). Based on low-temperature thermochronometry and seismic reflection data from the middle Magdalena Valley and field paleostress indicators, Parra et al. (2012) and Cortés et al. (2005) claim evidence for Paleocene to Eocene ENE–WSW contraction on the western flank of the present Eastern Cordillera.

4.2.1. Oligocene stresses

By Oligocene time, uplift and shortening of the Central Cordillera led to uplift in the foreland basin (now the western foothills of the Eastern Cordillera) (Horton et al., 2010; Moreno et al., 2011). Apatite fission-track and zircon (U–Th)/He 30 (ZHe) ages support an Oligocene age for the onset of deformation in the central axis of the Eastern Cordillera (Mora et al., 2010a; Saylor et al., 2012). Egbue and Kellogg (2012) estimate Late Oligocene shortening as 20% of the total Cenozoic shortening in the eastern foothills of the Eastern Cordillera. Hossack (1999) reported the presence of asymmetrical fracture sets (Fig. 7b) that appear to predate folding in the Cupiagua structure. This was done by removing those fractures that are related to folding from the fractures dataset. Prior to the subtraction, the fracture data was rotated so that the bedding is unfolded to the horizontal. Type 1

![Fig. 8. Eastern Cordillera uplift, shortening, and escape history (a) Uplift history of the Eastern Cordillera. Estimated paleoelevation of the Eastern Cordillera (black squares with error bars after Wijninga, 1996; Gregory-Wodzicki, 2000) and tectonic uplift (red lines). Tectonic uplift is estimated from present day total uplift (10 km) for erosion rates of 0.5 and 1.0 mm/a. (b) Estimated shortening rates for the Eastern Cordillera since Panama–South America collision began and northea...](#)
and type 2 fracture sets were removed from all the fracture data, a process which is similar to backstripping. Two less well developed fracture sets remain that are orthogonal: a WSW–ENE and a NNW–SSE trend. Since these fractures remain after the bedding dips on the different parts of the fold are unfolded back to horizontal, they are interpreted as predating folding of the Cupiagua structure. Orthogonal fracture sets of this type are not uncommon, and are typically found in undeformed foreland areas in front of thrust belts. Some examples are the fracture sets of the Appalachian Plateau (Engelder and Geiser, 1980), the Alberta foreland (Babcock, 1974), and the European Platform from the Alps to as far as southern England (Bevan and Hancock, 1986). In all cases, a main fracture set is usually orthogonal to the thrust belt and a second set lies at right angles to the main set. Younes and Engelder (1999) have shown that the earliest fractures in the Appalachian plateau developed prior to a major phase of layer parallel shortening. Continued shortening and detachment sliding of the cover rocks developed a new set of fractures that are slightly rotated compared to the earlier set. If we assume that the orthogonal fractures in the Cupiagua field are analogous to the Appalachian fracture sets, then it is possible that they could have formed during an earlier phase of layer-parallel shortening (Hossack, 1999). On the other hand, this E–W to ENE–WSW stress orientation is the same as that observed in the present-day stress field associated with the northeastward “escape” of the northern Andes, and the two may therefore be confused.

4.2.2. Andean stresses (Miocene to Present)

Paleobotanical data (Fig. 8a; Wijninga, 1996; Gregory-Wodzicki, 2000) and fission-track ages (Mora, 2007; Mora et al., 2010b) indicate that most of the uplift in the central and eastern flank of the Eastern Cordillera occurred in the last 10 Ma. Tectonic uplift (Fig. 8a) is estimated from present-day total uplift and paleoelevation data. Elevation is shown in black with present mean elevation just over 3 km and estimated paleoelevation based on paleobotanical and geomorphological data (black squares with error bars after Wijninga, 1996; Gregory-Wodzicki, 2000). Tectonic uplift (red line in online version) is estimated using present day total structural relief (10 km) and assuming erosion rates of 0.5 and 1.0 mm/a. Neogene exhumation history from apatite fission track data and low-T thermochronology (Mora, 2007; Parra et al., 2009) supports the continued rapid tectonic uplift proposed for the last 3 Ma. Using apatite fission-track data, Mora et al. (2010a,b) estimated exhumation rates of 1–1.5 mm/a for compressional structures in the eastern foothills of the Eastern Cordillera over the last 3 Ma. Wittmann et al. (2011) used cosmogenic nuclide-based measurements to estimate denudation rates of 0.49–1.2 mm/a for the Ecuadorian Andes. Note that the uplift curve for an erosion rate of 0.5 mm/a shows tectonic uplift in the Eastern Cordillera distributed over at least 10 Ma.

The shortening rates for the Eastern Cordillera (Fig. 8b; Egbue and Kellogg, 2012) since 12 Ma (the initiation of the Panama–South America collision) are estimated from the tectonic uplift rates
(Fig. 8a) and constrained to fit the present GPS measured rate, 12 ± 4 mm/a (Trenkamp et al., 2002). Shortening rates \( v \) are assumed to be proportional to tectonic uplift rates \( u \): \( v = ku \), where \( k \) is a dimensionless proportionality constant. Shortening rates are shown for a total shortening of 120 km in the last 12 Ma (0.8 × 150 km; Dendo and Covey, 1993; Egbue and Kellogg, 2012). For 120 km shortening, \( k = 18 \). Shortening rates are also shown for 60 km shortening, the minimum published estimate for the Eastern Cordillera (0.8 × 68 km; Cooper et al., 1995), where \( k = 9 \). North-eastward escape rates for the North Andean block (Fig. 8b) are from the compilation by Egbue and Kellogg (2010). The present-day Panama–South America convergence rate is approximately 30 mm/yr (Trenkamp et al., 2002). Note that range-parallel shear “escape” has become an important factor in the last 2 Ma, but range-normal shortening rates exceed the shear rates, and total shortening is 3–6 times as great as the shear displacement in the last 12 Ma.

About 12–15 Ma the Panama arc began colliding with the northern Andes (Coates et al., 2004; Montes et al., 2012), and the Eastern Cordillera became a major sediment source (Gregory-Wodzicki, 2000), although some sediments were being supplied to the Eastern Foothills area as early as the Oligocene (Mora et al., 2010a; Saylor et al., 2012). During the Andean stage (Miocene to Present) of deformation (Fig. 9a), thrusting and folding in the region generated most of the Eastern Cordillera and foothills structures orthogonal to the main stress and developing fold-related conjugate fractures. Two sets of fractures, symmetrically orientated to the fold hinges of the Cupiagua structure, form a strike-parallel type 2 fracture set and a strike-normal type 1 fracture set. A rotation of the shortening direction to a direction normal to the Cusiana (and Cupiagua structures (Fig. 3)) probably occurred as the thrust front advanced into the Llanos foothills (Hossack, 1999) (Fig. 10). Subsequent thrusting and folding generated the type 1 and type 2 fractures which were then superposed onto the earlier orthogonal set. The orientation of structures in the Piedemonte hydrocarbon block located northeast of the Cupiagua field, as seen on 3-D seismic reflection depth slices (Fig. 11), shows evidence of this late stage thrusting. The structures are oriented perpendicular to the NW–SE present-day maximum principal stress direction in the Eastern Cordillera.

4.2.3. Early Pleistocene range-parallel shear

By Early Pleistocene (Figs. 8 and 9b), in addition to the compressional stress regime, a NE–SW strike-slip component was introduced as the northern Andes began to “escape”. About 2 Ma, the aseismic Carnegie ridge, which was formed by the Galapagos
Fig. 11. 3-D seismic reflection depth slices through the Piedemonte block showing the orientation of major structural features at (a) 2270 m, (b) 4300 m, and (c) 5280 m.
hotspot, arrived at the Colombia—Ecuador trench (Lonsdale and Kligord, 1978; Pedoja, 2003; Cantalamessa and Di Celma, 2004), and initiated the northeastward “escape” of the northern Andes (Egbue and Kellogg, 2010). This resulted in the development of asymmetrical shear fractures oriented E–W to WSW–ENE and NNW–SSE similar to the fractures interpreted by Hossack (1999) as predating the folding. Presently, in the Eastern Cordillera the escape rate is almost as great as the rate of shortening due to the collision with Panama (Trenkamp et al., 2002; Egbue and Kellogg, 2012). However, since compressive strain results in higher stresses than shear strain, range normal compression still dominates the stress field in the Eastern Cordillera.

5. Conclusions

Borehole breakouts and seismic focal mechanisms indicate two present-day principal stress directions in the Eastern Cordillera; WNW–ESE to NW–SE, aligned with the GPS measured Panama—North Andes collision, and E–W to WSW–ENE, aligned with the northeastward “escape” of the North Andes. The Panama collision has produced most of the folding, shortening, and uplift of the Eastern Cordillera. The dominant fracture systems observed in the Cupiagua fold structures on the eastern flank of the Eastern Cordillera are produced by the collision and range-normal compression. Less well developed asymmetrical shear fractures oriented E–W to WSW–ENE and NNW–SSE may be related to pre-folding stresses in the foreland basin of the Central Cordillera (future Eastern Cordillera) or to present-day shear associated with the northeastward “escape” of the north Andean block. However, range-normal compression still dominates the stress field in the Eastern Cordillera. Our study suggests that the critical driver for orogenic deformation at transpressive plate boundaries is the increased coupling associated with the subduction of aseismic ridges and island arc collisions. Both range-normal shortening and range-parallel shear displacement must be considered when estimating the earthquake hazard for the Eastern Cordillera and the populous Bogota area.

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References


