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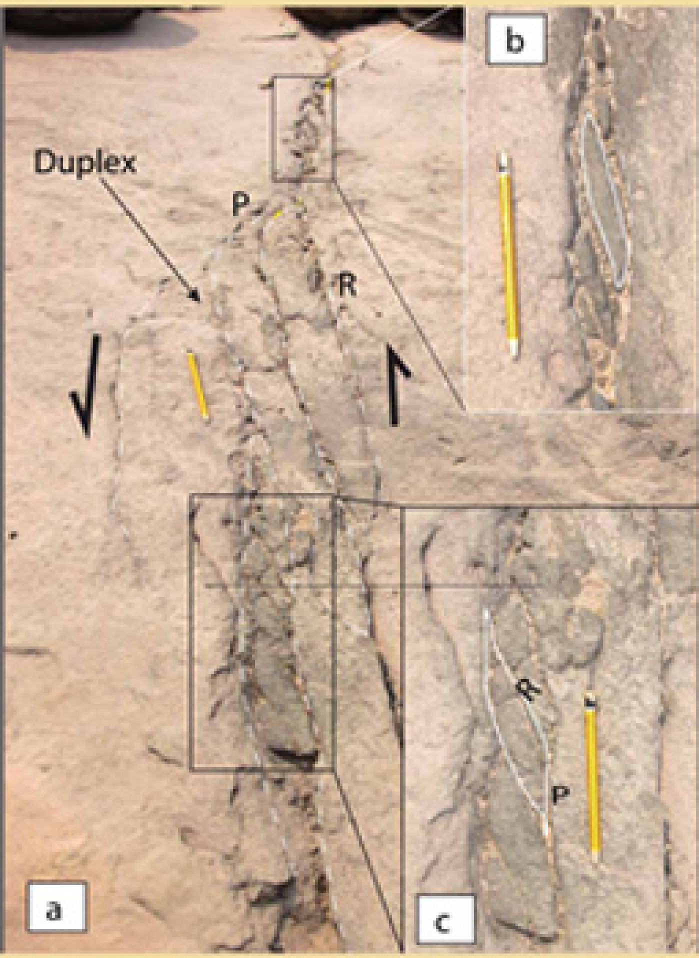

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Outcrop scale extensional duplex structures associated with strike-slip faults in sandstone of the Inkisi Group Brazzaville, Republic of Congo. *(See Nkodia et al., 531-550 for details.)*

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Flower structures in sandstones of the Paleozoic Inkisi Group (Brazzaville, Republic of Congo): evidence for two major strike-slip fault systems and geodynamic implications

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Abstract

Few studies have reported field descriptions of flower structures associated with strike-slip faults. This study describes and illustrates flower structures near Brazzaville (Republic of Congo) and explains their implication for the tectonic history of the Paleozoic Inkisi Group. Field observations show that the Inkisi Group is affected by two major strike-slip fault systems. The oldest system is dominated by north-northwest–south-southeast striking sinistral strike-slip faults and minor east–west striking dextral strike-slip faults. The youngest system consists of dominant northeast–southwest striking dextral strike-slip faults and minor northwest–southeast striking sinistral strike-slip faults. Flower structures within these major strike slip faults show four types of arrangements that likely depend on fault growth, propagation and damage zones: (i) flower structures associated with wall damage zones; (ii) flower structures associated with linking damage zones; (iii) flower structures associated with tip damage zones; and (iv) “hourglass” flower structures.

Paleostress analysis reveals that both major fault systems originated from two differently oriented pure strike-slip regime stress stages. The first stage, which engendered the first major fault system, developed under northwest–southeast compression (i.e, $\sigma_1 = 322°$). This phase probably coincided with north–south collision in the southern part of Gondwana in the Permo-Triassic and the Late Cretaceous compression times. The second stress stage, creating the second major fault system, developed under east–west (i.e, $\sigma_1 = 078°$) compression. This phase is correlated with compression from the east–west opening of the Atlantic Ocean in the Miocene times.

Introduction

Although flower structures and duplexes associated with strike-slip dominated deformation regimes have been treated theoretically or have been interpreted in seismic profiles (Sanderson and Marchini, 1984; Fossen and Tikoff, 1998; Jones and Holdsworth, 1998; Lin et al., 1998; Deng et al., 2019), field examples are less documented in the literature, particularly in a pure strike-slip regime. Thus, characterizing field examples of flower structures would provide a better understanding of the structural style of strike-slip deformation, as ambiguity arises for similar structures associated with dip-slip faults (Coward, 1996; Corbett, 1999).

The Inkisi fault systems near Brazzaville in the Republic of Congo recently reported by Delvaux et al. (2017, 2014); Nkodia (2017), Miyouna et al. (2018), provide a field laboratory of detailed 100 to 400 m strike-slip structures, including flower structures, that help to infer the tectonic history of the Inkisi Group. This tectonic history has been discussed in the past with differing conclusions (Cornet and Pourret, 1982; Alvarez et al., 1995). In previous studies (e.g., Miyouna et al., 2018), flower structures were not thoroughly taken into consideration in conclusions regarding the deformation history. Furthermore, the principal paleostress orientations were not well-constrained in previous studies.

This study seeks first to characterize flower structures and their implication for the tectonic history associated with the Inkisi Group fault systems, and then to provide a paleostress analysis of the Brazzaville area. Furthermore, the paper will provide easier identification of flower structures, as closely similar structures appear in association with reverse and normal faults, and thereby aid in structural interpretation. Additionally, as flower structures, duplexes, and restraining and releasing bends constitute potential hydrocarbon traps in strike-slip regimes (Cunningham and Mann, 2007), this study will be useful in hydrocarbon exploration as similar structures have been found in units of the Congo Basin (Daly et al., 1992; Kadima et al., 2011).

Geological setting

The Paleozoic Inkisi Group is an arkose unit exposed in the southwest area of the Republic of Congo (RC) (Figure 1). This unit has also been described in Angola (Staton et al., 1963; Schermerhorn, 1981) and the Democratic Republic of Congo (DRC) (Cahen and Lepersonne, 1966; Cahen, 1982; Tack et al., 2001; Delpomdor and Préat, 2015; Delpomdor et al., 2019). Inkisi Group sandstones reach 600 to 700 m of thickness

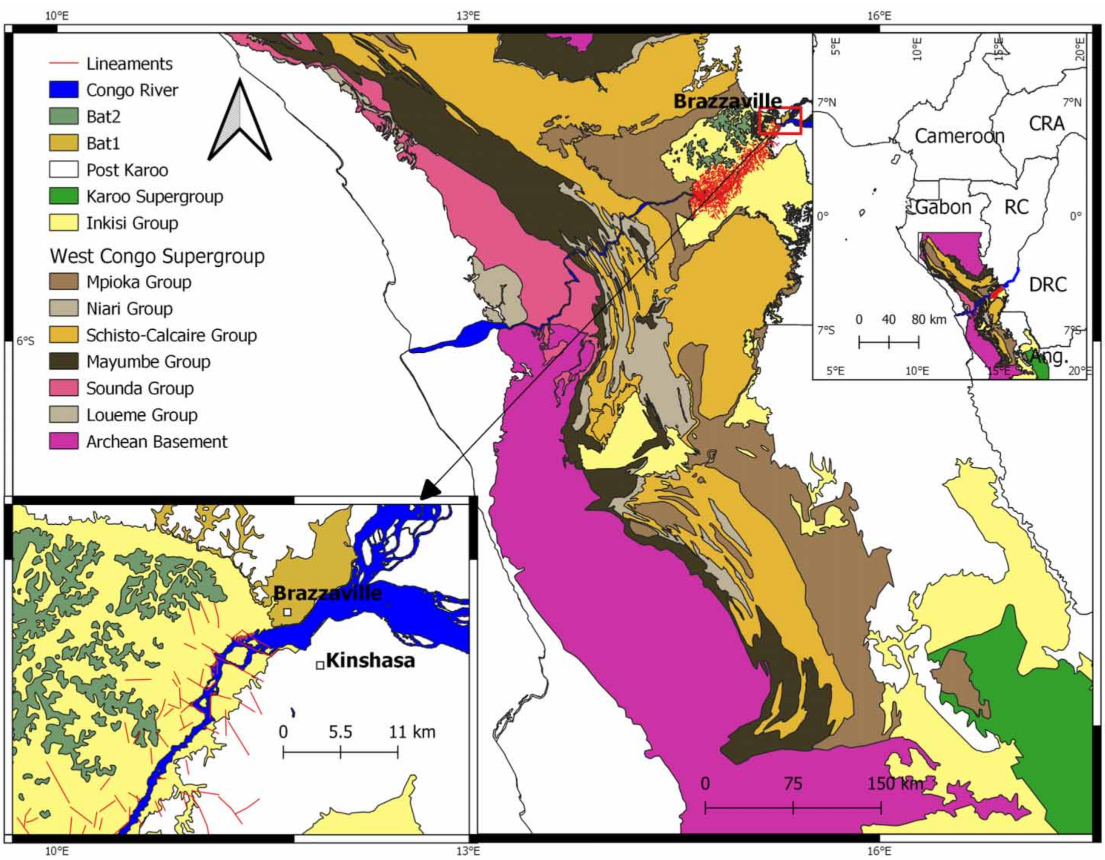


Figure 1. Map showing the distribution of Inkisi Group in central Africa and the study area in Brazzaville along the Congo River. RC=Republic of Congo, DRC=Democratic Republic of Congo. Compiled after Fernandez-Alonso et al. (2017) and Callec et al. (2015).

(Dadet, 1969). These arkose units are essentially composed of rhythmic sequences of coarse red sandstones, followed by fine sandstones and claystone. Sandstones of the Inkisi Group have been interpreted to be of fluvial origin (Boudzoumou, 1986; Callec et al., 2015).

Previous studies considered the Inkisi Group as part of the West-Congo Belt (Cahen and Lepersonne, 1966; Dadet, 1969; Hossié, 1980; Boudzoumou, 1986; Boudzoumou and Trompette, 1988), but nowadays this Group is separated from the West-Congo, in the RC (Callec et al., 2015) and DRC (Tack et al., 2001) because it unconformably overlies the Mpioka unit, the youngest of the West Congo units (Figure 1). The Inkisi Group is unrelated to the Araçuaì-West-Congo orogeny (Figure 2), but the unconstrained age of the Inkisi Group makes this relationship problematic. We suggest that the Inkisi Group might have been deposited between Ordovician and pre-Permian times. We refer to three lines of reasoning from the literature to support this idea:

- By dating pre-collisional and syn-collisional granitoids, most studies showed that the shortening period during the collision in the Araçuaì-West-Congo orogen hinterland lasted 50 Ma, between 630 and 580 Ma (Pedrosa-Soares and Alkmim, 2011; Gonçalves et al., 2016; Peixoto et al., 2017). However, the timing of later stages of collision in the foreland part of the Araçuaì-West-Congo orogeny is not well constrained, including both shortening and the post-collisional phase. In the DRC, a late extensional event is recorded (Tack et al., 2018) at 524.6 ± 4.6 Ma (Ar-Ar age in quartz). In Brazil, the youngest unit of the Araçuaì orogen in the Bambui Group, called the Três Marias Formation, has been dated at 527 ± 4.6 Ma (U-Pb age from detrital zircon). This age implies that contractional deformation was still a factor after its maximum depositional age (Tavares et al., 2020). Additionally, a metamorphic event in Mpioka group has been dated of 499 ± 19 Ma (Fullgraf et al., 2015) from K-Ar datation and illite crystallinity analysis on white micas, which is contemporaneous with 490 Ma ages in Angola (Monié et al., 2012). This implies that the shortening period of the Araçuaì-West-Congo orogeny would have lasted at least 150 Myr probably until the late Cambrian. Then, the Inkisi Group would be post- Cambrian.
- Most authors (Frimmel et al., 2006; Tack et al., 2008, 2018; Straathof, 2011; Affaton et al., 2016) agree that Inkisi Group is unrelated to the Araçuaì-West-Congo orogeny. In the RC, U-Pb ages from detrital zircon demonstrate that this formation was deposited later than ca. 600 Ma (Affaton et al., 2016). In the DRC, the maximum depositional age of the Inkisi Group is constrained at 558 ± 29 Ma (U-Pb age from detrital zircon), which is similar to the age of 581 ± 29 Ma (U-Pb age on zircon) obtained by Straathof (2011). However, later deformation of the West Congo orogen has been recorded until 490 Ma in Angola (Monié et al., 2012) and in RC (Fullgraf et al., 2015). This would place the Inkisi Group younger than the Cambrian.
- Karoo deposits overlie the Inkisi Group in Angola. These Karoo deposits are of Permian age (Oesterlen and Tessensohn, 1976; Oesterlen, 1979, 1980). The term "Karoo," derived from the main Karoo Basin of southern Africa containing Late Carboniferous to Middle Jurassic sediments, is used to describe deposits of similar age across Gondwana (Ring, 1995; Catuneanu et al., 2005). Therefore, the Inkisi Group must be Pre-Permian.

The Inkisi Group has been correlated to "redbeds" sequences of the Congo basin (Tack et al., 2008) in central Africa. These so-called redbeds are 1000 m thick and constitute the Banalia Group in the Lindi Basin in the RDC and the Banio Group in the Central African Republic (CAR). They unconformably overlie folded Neoproterozoic rocks of the Pan-African West Congo and Katanga belts, thus they are post *ca.* 550 Ma in age (paroxysm of Pan African orogeny) (Tack et al., 2008; Tait et al., 2011; Linol et al., 2015). These redbeds are siliciclastic units and comprise a large volume of reddish-violet arkoses (Tack et al., 2008) with similar sedimentary structures as those observed in the Inkisi Group. They have also been shown to contain remnants of Placoderm fossils of Devonian age (Tack et al., 2008).

In Brazzaville (RC), the Inkisi Group is overlain by the Stanley Pool Group of unknown age in Brazzaville. The Stanley Pool is only seen in the subsurface in Brazzaville. It is essentially composed of sandstones and shales (Callec et al., 2015). The Stanley Pool Group is followed by sands and sandstones of the Batéké Group (Callec et al., 2015). The Batéké is comprised of Bat1 and Bat2 units that outcrop in the Batéké Plateaux of Brazzaville. They are frequently found on the top of the Inkisi Group. The Bat1 has a minimum deposition age (Callec et al., 2015) of 279.8 ± 7.1 Ma (Permian, U-Pb on zircon) and consists of hard sandstones, whereas Bat2 consists primarily of loose sands.

Regional Framework and tectonic evolution of central Africa

The Inkisi Group is surrounded by large geotectonic features in central Africa (Figure 3). The geological framework and the distribution of the Inkisi Group in the study area evolved in several tectonic phases. In the southwestern part of central Africa, the Inkisi Goup is limited by the West-Congo belt (630 to 490 Ma), an orogen that is part of the Pan-African orogenic cycle that led to the assembly of West Gondwana. In the northwest, the Inkisi Group is bounded by the Ntem and Chaillu cratonic blocks of Archean to Proterozoic age (Moloto-A-Kenguemba et al., 2008; Pedreira and De Waele, 2008). These cratonic blocks constitute the borders of the east–west Yaouandé-Obanguides belt (640 to 540 Ma) in northern Cameroon (Ngako et al., 2003). This belt developed the dextral Central African shear zone (CASZ) (Cornacchia and Dars, 1983; Ngangom, 1983) that controlled the development of the Pan-African orogeny in Cameroon. The CASZ has 40 km of displacement (Cornacchia and Dars, 1983) and extends at least 2000 km from the Gulf of Guinea through Cameroon, Chad, and the Central African Republic, and into Sudan (Cornacchia and Dars, 1983; Maurin et al., 1986). This shear zone was reactivated during the opening of the Central Equatorial Atlantic rift in the Late Cretaceous (Fairhead, 1988; Guiraud and Maurin, 1991). The opening of the Atlantic Ocean was accommodated in

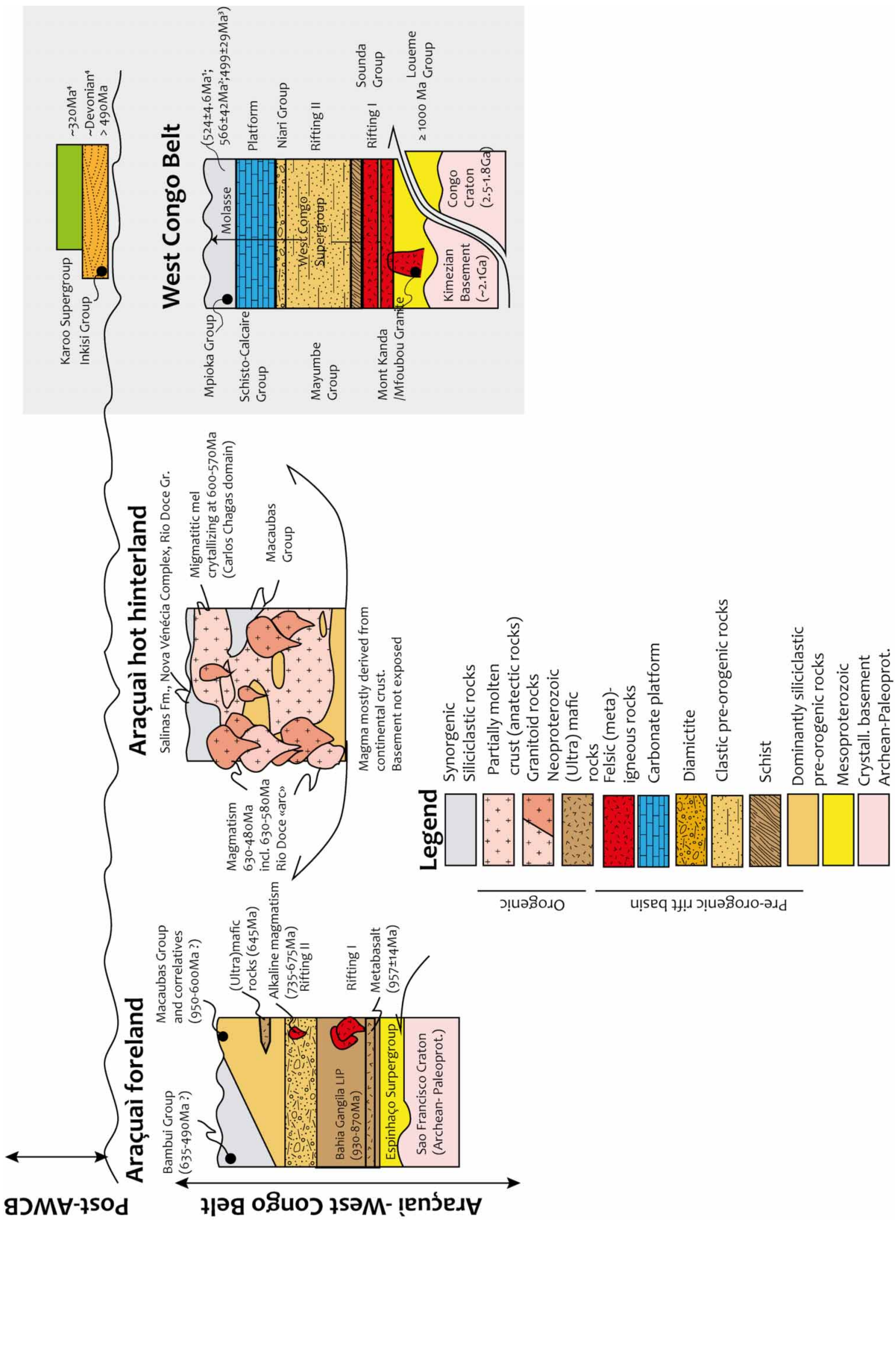


Figure 2. *Relationship between Inkisi Group and the Araçuaì-West-Congo belts. Modified after Konopásek et al. (2020).*

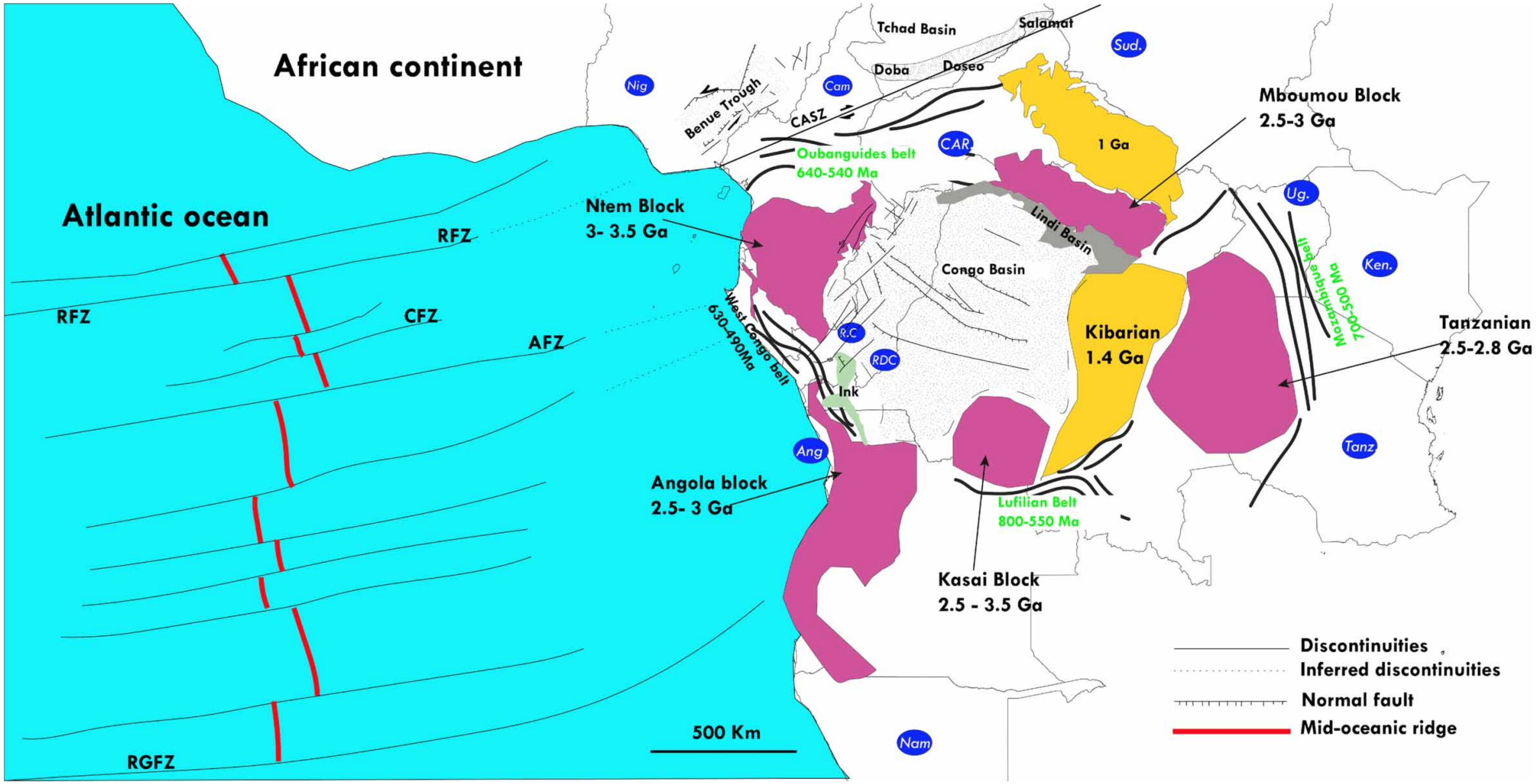


Figure 3. *Geotectonic units around the Inkisi Group in Central Africa. RFZ, CFZ, AFZ and RGFZ, respectively the transforming fault zones of Romanche, Chain, Ascension and Rio de Grande, Ink=Inkisi Group. Nig=Nigeria, Cam=Cameroun, CAR=Central African Republic, Sud=Sudan, Ug=Ugunda, Ken=Kenya, Tanz=Tanzania, Nam=Namibia, Ang=Angola, RC=Republic of Congo, DRC=Democratic Republic of Congo. The areas of discontinuities come from the work of Saba (2014). The transforming faults were redrawn from the work of Heine et al. (2013).*

central Africa and northeastern Brazil by reactivation of several fracture zones and the development of intracontinental basins (Guiraud et al., 2005; Moulin et al., 2010) such as the Benue trough in Nigeria (Benkhelil, 1982; Guiraud et al., 1989; Igwe and Okonkwo, 2016) and the Doba, Doseo, and Salamat basins in Chad (Figure 3) (Genik, 1992). In the northeast and to the east, the Inkisi Group is covered by Congo Basin deposits. This large basin has recorded evidence of the Pan-African orogeny and Gondwanide far-field stress propagation from the southern margin of Gondwana in the Permo-Triassic (Daly et al., 1991, 1992; Giresse, 2005; Kadima et al., 2011). The Pan-African orogeny only affected Neoproterozoic sediments while the Gondwanide collision affected only Karoo and redbed deposits of the Congo basin (Kadima et al., 2011). In central Africa, Karoo deposits in the Congo Basin are referred to as the Lukaga Formation and the Haute Lueki Formation (Lepersonne, 1977; Cahen and Lepersonne, 1978; Linol et al., 2016). Most of these Karoo deposits are deformed; their deformation is related to north–south shortening from far-field stresses generated by the late Permian to early Triassic development of the Cape Fold Belt (Daly et al., 1991; Kipata et al., 2013).

Recent studies of the Inkisi Group reported two phases of strike-slip deformation in the area of Brazzaville and Kinshasa (Delvaux et al., 2014, 2017; Nkodia, 2017; Miyouna et al., 2018). The first phase formed joints which evolved dominantly into sinistral strike-slip faults of northwest–southeast to north–south direction (348° average direction). The evolution of joints into strike-slip faults required a slight change of the stress orientations of 10° westward (Miyouna et al., 2018). The second phase also formed joints which evolved predominantly into dextral strike-slip faults of northeast–southwest direction (45° average direction). In this phase the passage from joints into strike-slip faults required also a slight change in stress orientation, but this time of 10° eastward (Miyouna et al., 2018).

The temporal offset between the two fault systems has not been clear in Brazzaville (Miyouna et al., 2018). The two phases have mainly created the same types of variable secondary structures along their traces, including horse-tail terminations, extension fractures, en-echelon fractures, pull-apart structures, and flower structures. Those structures are distributed along different parts (tips, relay zones and walls) of fault damage zones as described by Kim et al. (2004). However, the description of flower structures found in the Inkisi Group have previously not been taken properly into account, and we show here that they are critical structures for understanding the strike-slip deformation.

Overview of flower structures

Strike-slip faults often do not show straight traces in either cross-section or plan view. In cross-section, they often develop an array of upward-diverging fault splays called flower structures. Flower structures can be defined as faults arrayed in a delimited space (kilometers to millimeters) in profile view, that merge at depth into a sub-vertical fault (Harding and Lowell, 1979) (Figure 4). Concave-up geometries have been referred to as tulip structures or negative flower structures (Naylor et al., 1986), while convex-up geometries have been called palm tree structures or positive flower structures (Sylvester, 1988).

The development of flower structures results from a shortening or extension component being associated with movement along strike-slip faults. When flower structures are associated with an extensional or compressive component, they are classified as negative or positive respectively (Wilcox et al., 1973). However, the distinction of the dip-slip component of the movement is not always obvious to recognize along the strike-slip fault (Woodcock and Rickards, 2003).

We will use the terminology of Kim et al. (2004) and Woodcock and Fischer (1986), who synthesized and classified structures and geometries that appear with strike-slip faults in plan and cross-section views (Figure 4).

The map view expression of flower structures has been associated with duplexes occurring along strike-slip faults (Woodcock and Fischer, 1986; Woodcock and Rickards, 2003). Duplexes may develop at straight segments of faults by the successive connection of P and Y-shears or Y and R-shear fractures (Bartlett et al., 1981), or at the bends or relays by successive horst cuts (Woodcock and Fischer, 1986) (Figure 4).

Methodology

The data come from sandstone quarries (Brossette and Kombé) located southwest of Brazzaville (Republic of Congo) along the Congo River, where we distinguished different types of flower structures and analyzed their relationships with the main strike-slip faults observed. An idealized three-dimensional geometry of flower structures in the Inkisi Group has been defined.

Based on a collection of 394 fault slip data points, the stress regime has been determine by using an inverse method through the Win-Tensor program (Delvaux, 2012). Fault slip data are used to reconstruct the four parameters (σ_1, σ_2, σ_3 and $R = (\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$) of the reduced tectonic stress tensor assuming that slip on the plane occurs in the direction of the maximum resolved stress (Wallace, 1951; Bott, 1959). After the validation of data, the program uses the PBT kinematic axes (P for contractional axis, T for extensional axis, B for intermediate axis) (Marrett and Allmendinger, 1990) or Right Dihedron methods (Angelier and Mechler, 1977) to determine a preliminary stress tensor. The latter serves as a starting point in the Rotational Optimization method which executes an iterative testing of a number of solutions using a rotational strategy. The program generates a misfit function (F5 in Win-Tensor) that minimizes the misfit angle between the observed and the resolved slip lines for each fault in the stress tensor applied on fault slip data. The quality of the result is evaluated using the quality parameter for fault slip data inversion (Delvaux and Sperner, 2003). The stress regime is expressed by computing an index regime called R′, based on the ratio R and the nature of most subvertical axes (Delvaux et al., 1997; Delvaux and Sperner, 2003). The index R’ is expressed by a vertical continuous scale from 0 to 3, with $R' = R$ for an extension regime (0 to 1); $R' = 2 - R$ for a strike-slip regime (1 to 2); $R' = 2 + R$ for a thrust regime (2 to 3).

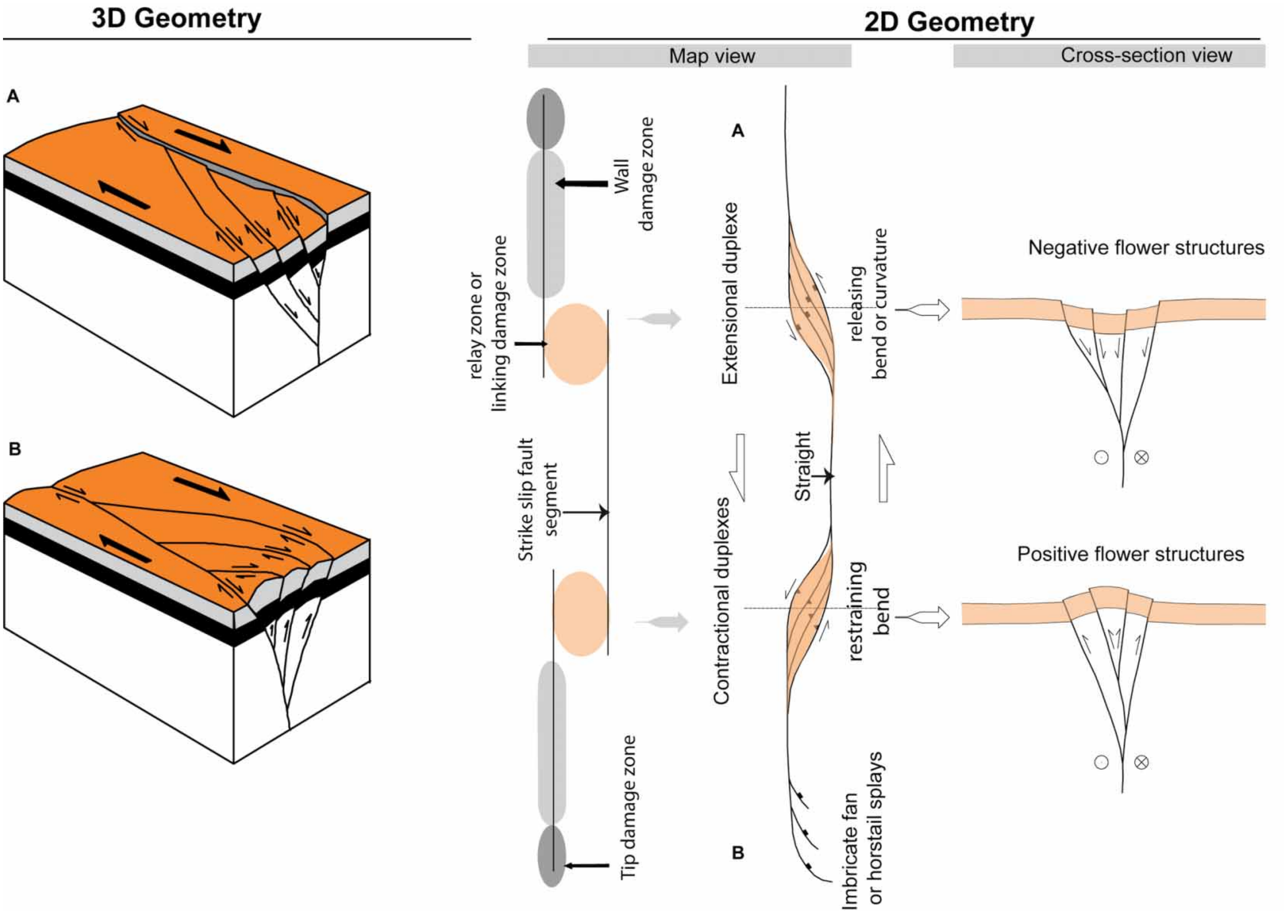


Figure 4. *3D and 2D geometry of flower structures and terminology of structures and types of fault damage zones. Profile and plan view expression of flower structures. Compiled from Woodcock and Fischer (1986); Woodcock and Rickards (2003); Kim et al. (2004).*

In the field, we defined two fault systems. Both systems were identified based on field criteria including offset features, orientation of inferred maximum principal stress axis (σ_1) from extension fractures, and conjugate faults (Olson and Pollard, 1989; Angelier, 1994). A semi-automatic grouping was then performed with the assistance of the Win-Tensor program. The program calculates the misfit angle between the observed and the model slip lines of each fault in a group, to see whether the mapped fault plane is consistent with a tensor found by the program or is more likely associated with another tensor. Fault planes that result in a high-misfit angle are rejected by the program, meaning those faults are more likely associated with another tensor. When no tensor is found to explain their formation, the group of faults is simply rejected.

Results

Characterization of structures

Flower structures were studied along both fault systems previously described by the authors (Nkodia, 2017; Miyouna et al., 2018). The 394 faults studied were separated into two different fault systems in the field, called Z1 and Z2, respectively. The second fault system (Z2) offsets the first system (Z1) by 3 cm to 12 cm in the field (Figure 5). This offset is quite regular in the study area. Furthermore, two inferred stress orientations were obtained along conjugate faults observed in the field within these systems. One stress orientation was northwest–southeast for the first system; another was east–west for the second system of faults.

In map view (Figure 6), both systems are generally arranged in relay structures that exhibit both left and right stepping structures, although in some places they exhibit in-line patterns (parallel faults). Relay and tip zones of both systems generally develop extensional fractures, duplex, horsetail and flower structures in cross-section view. Each of these secondary structures shows a systematic arrangement in the field.

The first system (Z1) contains dominantly north-northwest–south-southeast to north–south (average strike of 345°) sinistral strike-slip faults, although some east–west dextral strike-slip faults also occur. The faults have steep dips and well-marked slickenlines (Figures 7a and 7b) that are expressed as calcite fibers on fault planes. The pitch of slip lines varies between 0° and 25°, with an average of 7° (Figure 7d). The Frohlich diagram shows that most of the faults of this group form in a pure strike-slip regime with a slight transpressional component (Figure 7f).

The second fault system (Z2) consists of mainly dextral strike-slip faults; however, some sinistral faults also occur, seeming to be conjugate to dextral faults. These faults are

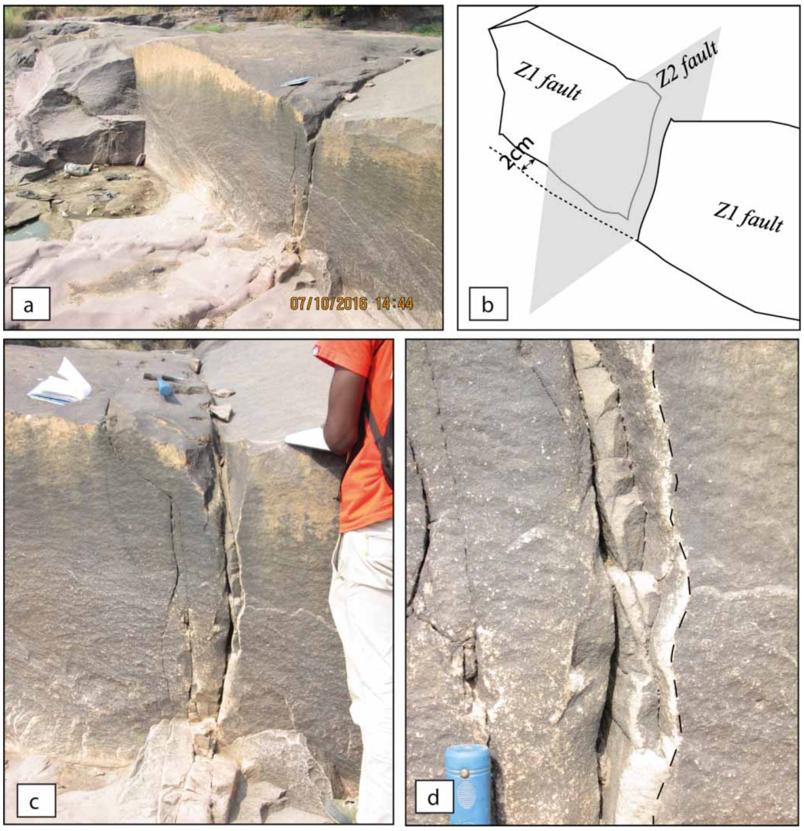


Figure 5. *Fault relationships and characteristics (**a**) and (**b**) the first fault system Z1 is offset by the second fault system Z2. (**c**) Oblique view relationship between Z1 and Z2 (**d**) dashed line indicating corrugation along Z1 fault.*

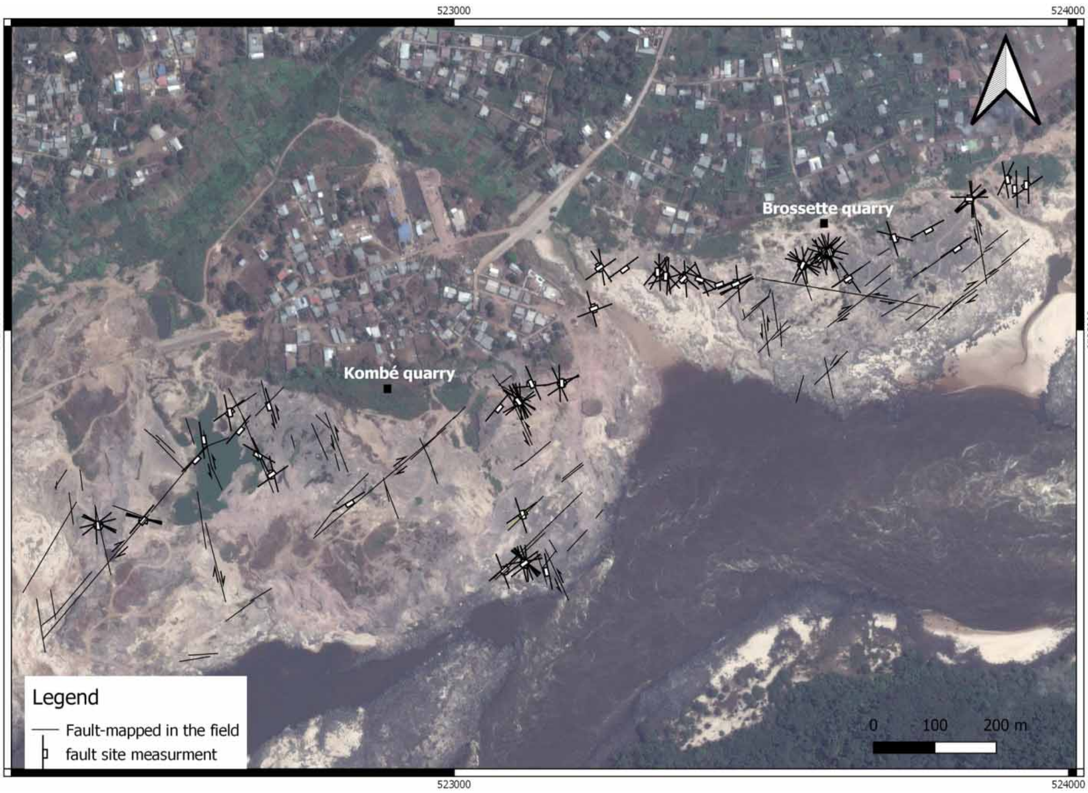


Figure 6. *Google Earth image from 1/08/2015 showing locations of fault measurements.*

generally oriented northeast–southwest (average strike of 048°) and have well-marked slickenlines (Figures 7g and 7h). The pitch found along that group varies from 0 to 15° (Figure 7j), with an average of 7°S. The Frohlich diagram shows that most of the faults of this group formed in a pure strike-slip regime with any apparent transtensional component being quite insignificant (Figure 7i).

Flower structures

We identified positive and negative flower structures along both fault systems. These structures also showed a systematic arrangement with the architecture of strike-slip faults in plan-view and cross-section view. Flower structures frequently appeared at the relay (stepover), duplex and tip zone, and also between two parallel faults with no connectivity zone.

Negative flower structures

In the field, negative flower structures (Figure 8) were found along the first fault system (Z1) and the second fault system (Z2). In cross-section view, negative flower structures show concave-upward shape. They are also identified from their array of fractures, with extensional fractures inclined at approximately 45° from major fractures, and displaced pebbles along their traces in cross-section which clearly show a normal displacement component of a few centimeters (Figure 8b). Some fault surfaces are accompanied by calcite and palygorskite fibers (Mees et al., 2019), together with well-marked sub-horizontal striations. (Figure 8c).

More unusual, some negative flower structures present an hourglass shape (Figure 9). This structure represents a site from which some fractures fan upward and others downward.

In plan-view, some flower structures show no or loosely-linked subparallel fractures (Figure 10a), while others show a wedge-shaped termination between two parallel faults (Figure 11e). All these fractures are linked in cross-section view along a single fault (Figure 10b). Some extensional duplex structures accompanied by extensional fractures have been observed along flower structures (Figures 10 and 11a), clearly reflecting the classical physiographic expression of negative flowers (Woodcock and Fischer, 1986).

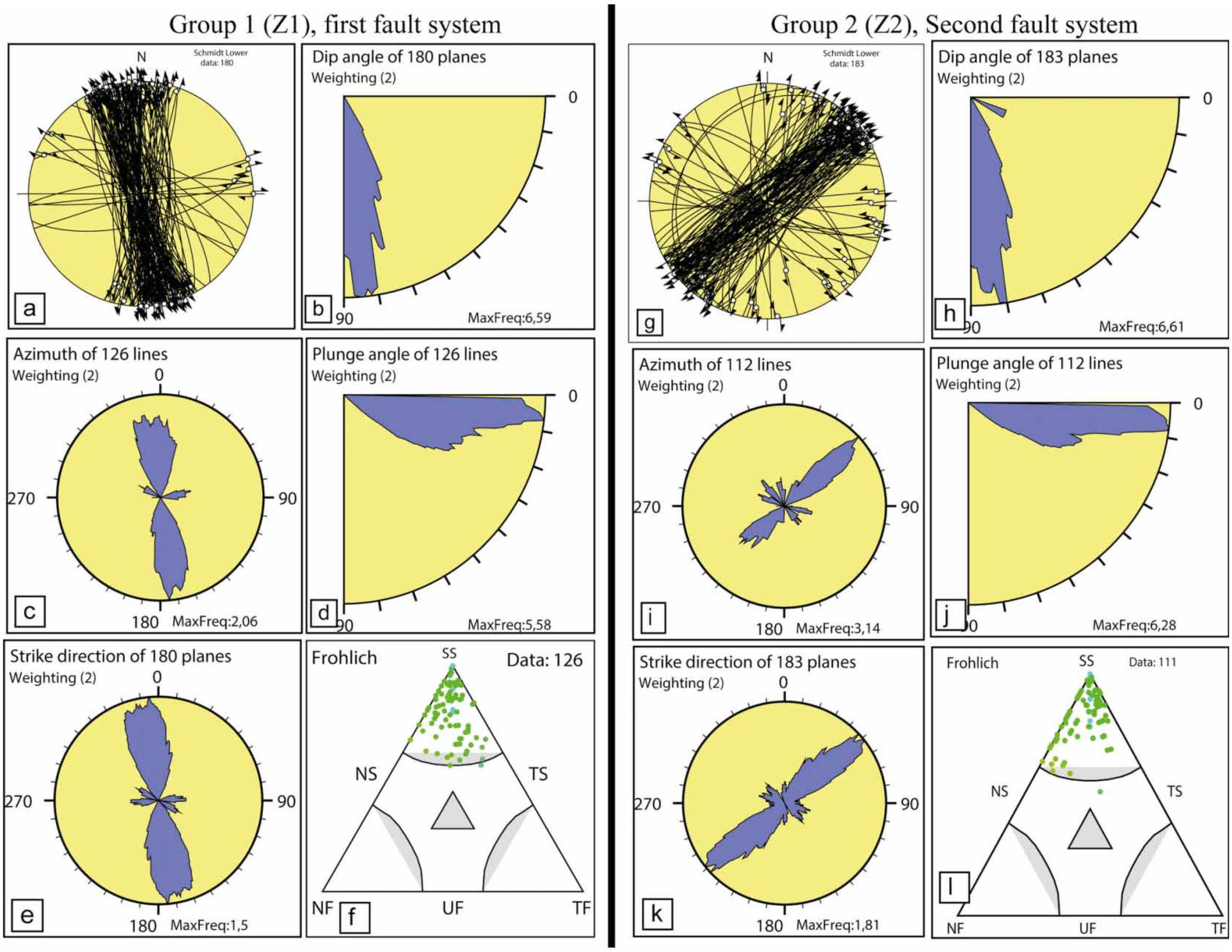


Figure 7. *Rose diagrams and Frohlich diagram of the two fault systems. NS=Normal-strike slip fault; TS=Thrust strike slip fault; NF=Normal fault; UF=unknown fault; TF=Thrust fault.*

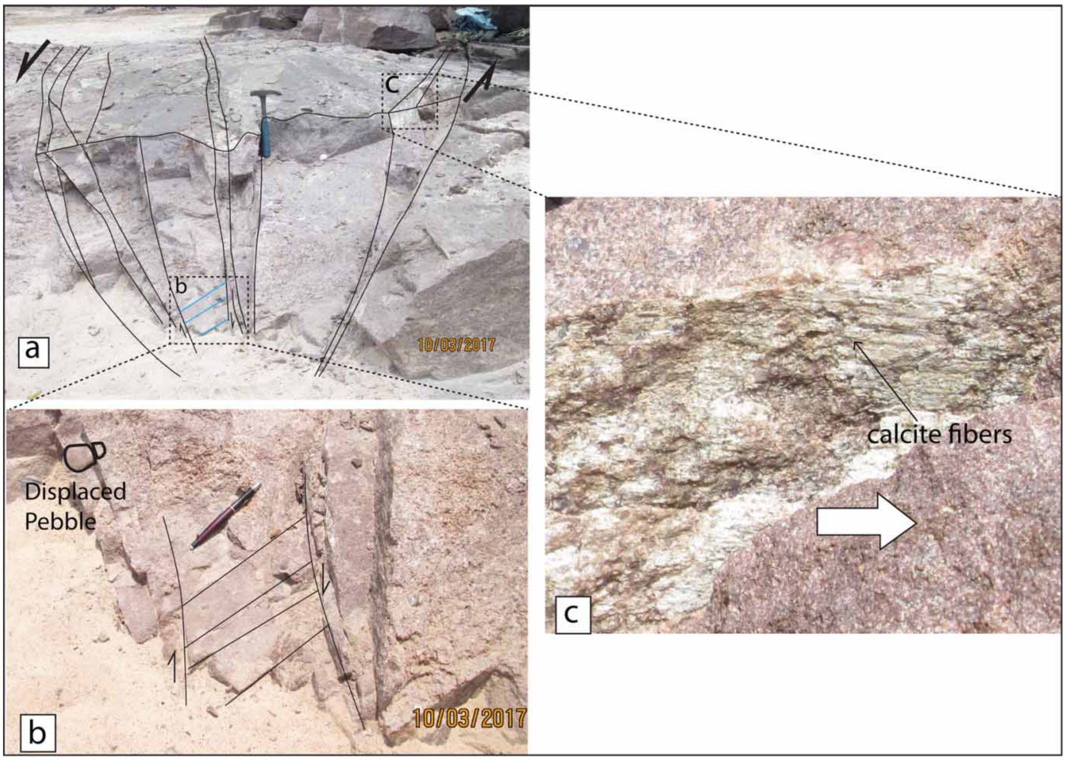


Figure 8. *Negative flower structures along a sinistral strike-slip fault (Z1). (**a**) Geometric view of a fault array associated with the negative flower structure. (**b**) Extensional fractures and displaced pebble within fault array. (**c**) Calcite fibers on faults surface.*

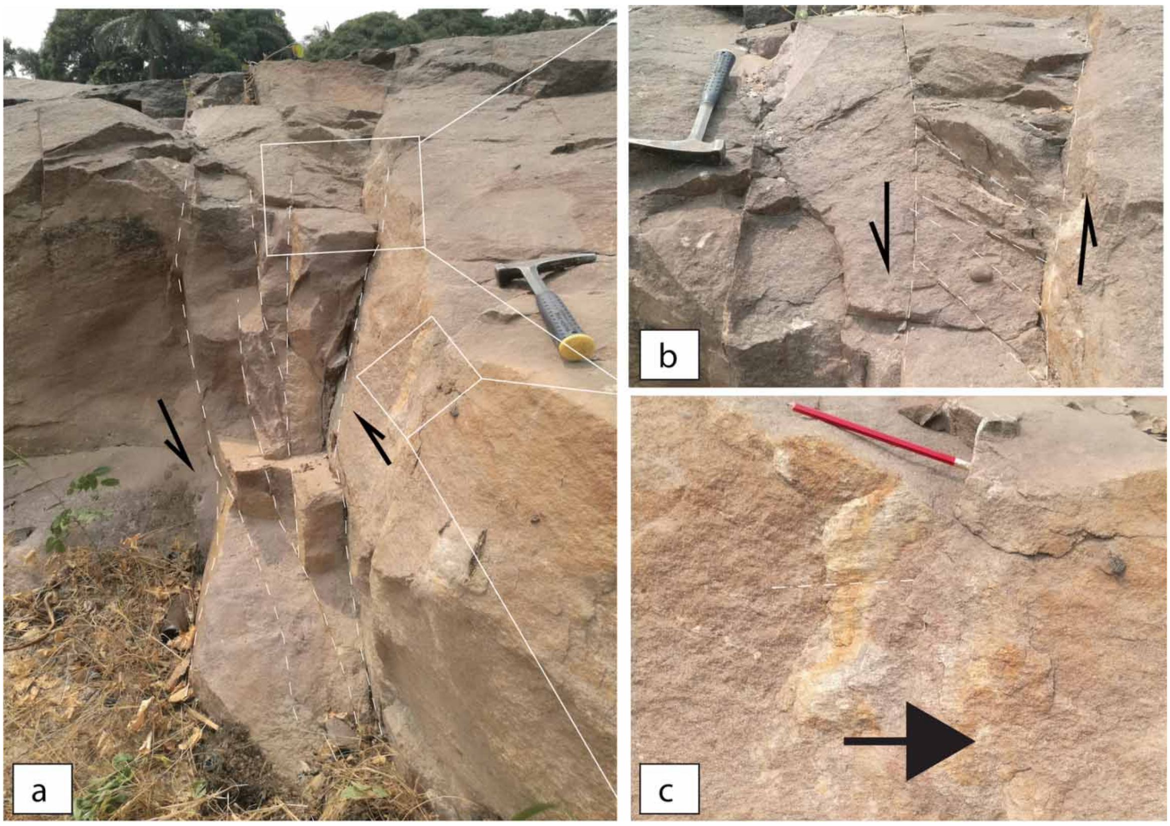


Figure 9. *Hourglass negative flower structures along a sinistral fault (Z1). (**a**) Cross-section view. (**b**) Extensional fractures between bounding strike-slip fault. (**c**) Subhorizontal slickenlines along the fault surface; the black arrow indicates the sense of movement of the missing block.*

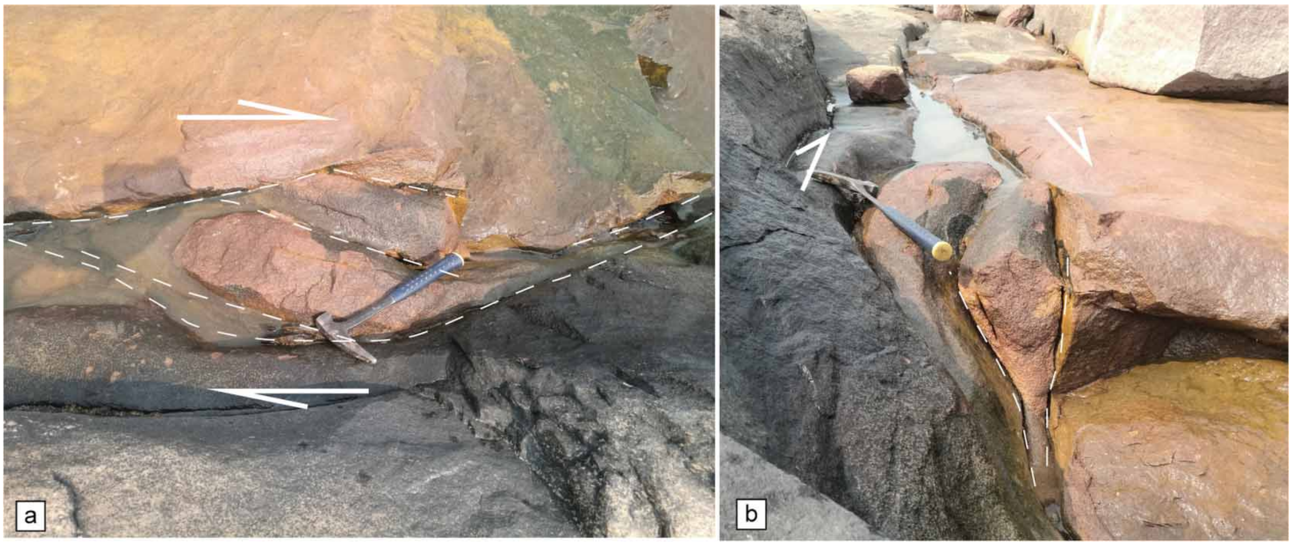


Figure 10. *Negative flower structure along a dextral strike-slip fault (Z2). (**a**) Plan view of the structures, showing an extensional strike-slip duplex. (**b**) Three-dimensional view showing negative flower structures.*

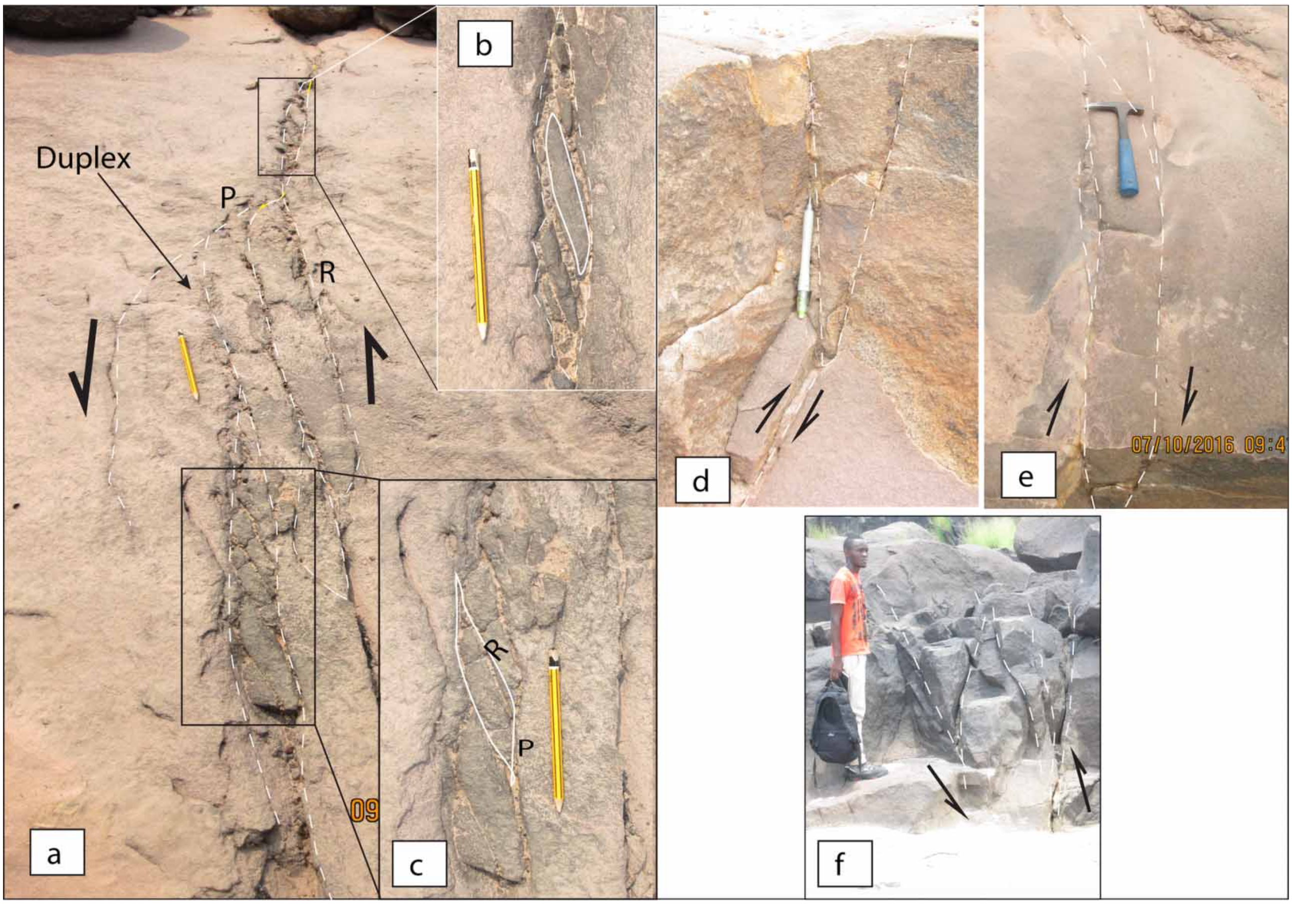


Figure 11. *(**a**) General view of a Riedel extensional duplex along a sinistral strike-slip fault (Z2), in map view. (**b**) and (**c**) Small lenses developed by the interaction of P and R. (**d**) Weakly developed flower structures in profile view (Z1). (**e**) Plan view of (d). (**f**) Moderately well-developed flower structure (Z1).*

Positive flower structures

Positive flower structures occur more frequently along the Z1-fault system than along the Z2-fault system. They are commonly associated with inclined striations having a 20° maximum pitch with sinistral faults. Furthermore, positive flower structures show a convex-upward shape (Figures 12c and 13b).

In plan-view, positive flower structures are sometimes located where contraction faults are bounded by two subparallel principal faults, or between an array of non-connected subparallel faults. Duplexes also showed positive flowers (Figure 12c). The plan view organization of flower structures seems systematic to the entire architecture of the strike slip system, as we also found flower structures at faults tips accompanied with en-échelon shear fractures (Figure 13) or extensional fractures.

Stress regime

From all 394 recorded data points along the two fault systems Z1 and Z2, we obtained two stress tensors. Thirty-one (7.8%) faults were "rejected" (Figure 14c), because they did not fit either geometrically or kinematically with the tensors of the Z1 or Z2 Groups.

The first tensor, obtained from the first fault system (Z1), indicates a regime at the transition from pure strike-slip to transpression, as R' = 1.7 (Delvaux et al., 1997). This regime was obtained from 126 fault-slip planes out of 180 fault-slip planes recorded, and shows northwest–southeast compression with a northeast–southwest extension. The quality parameters QRw and QRt are respectively good (C) and medium (D); we obtained the maximum compressive horizontal stress σ_1 322°(±6)/01 (Figure 14a).

The second tensor, determined from the second fault system, indicates an extensional to dominantly pure strike-slip regime (Figure 14b). It was calculated from 112 fault slips out of 183 recorded. The regime indicates east–west compression and north–south extension. The quality parameters QRw and QRt are both medium (C), suggesting a constrained tensor. The maximum compressive horizontal stress σ_1 is 078°(±0.3)/05, and the index ratio R' = 1.45, indicating a pure strike-slip regime with a small transtensional component.

Discussion
Flower structures

All the field observations highlight remarkable examples of small-scale flower structures, which are infrequent in the current literature as noted by Woodcock et al. Rickards (2003). The three-dimensional approach offers a better opportunity to understand the physiographic expression of flower structures in the field.

Two types of flower structures were observed, according to the component acting along the principal zone of displacement (PDZ). Negative flower structures show a broadly concave-upward shape in cross-section view (see Figure 8a) and a releasing bend or stepover in plan-view (see Figure 10), which are the common characteristics of negative flower structures as demonstrated by several authors (Bartlett et al., 1981; Sylvester, 1988; Dooley, 1994; Dooley and Schreurs, 2012). More importantly, some flower structures contain displaced pebbles or extensional fractures that helped determine the normal dip-slip component associated with the PDZ. In the area where negative or positive flower structures were difficult to determine from the shape or stratigraphic

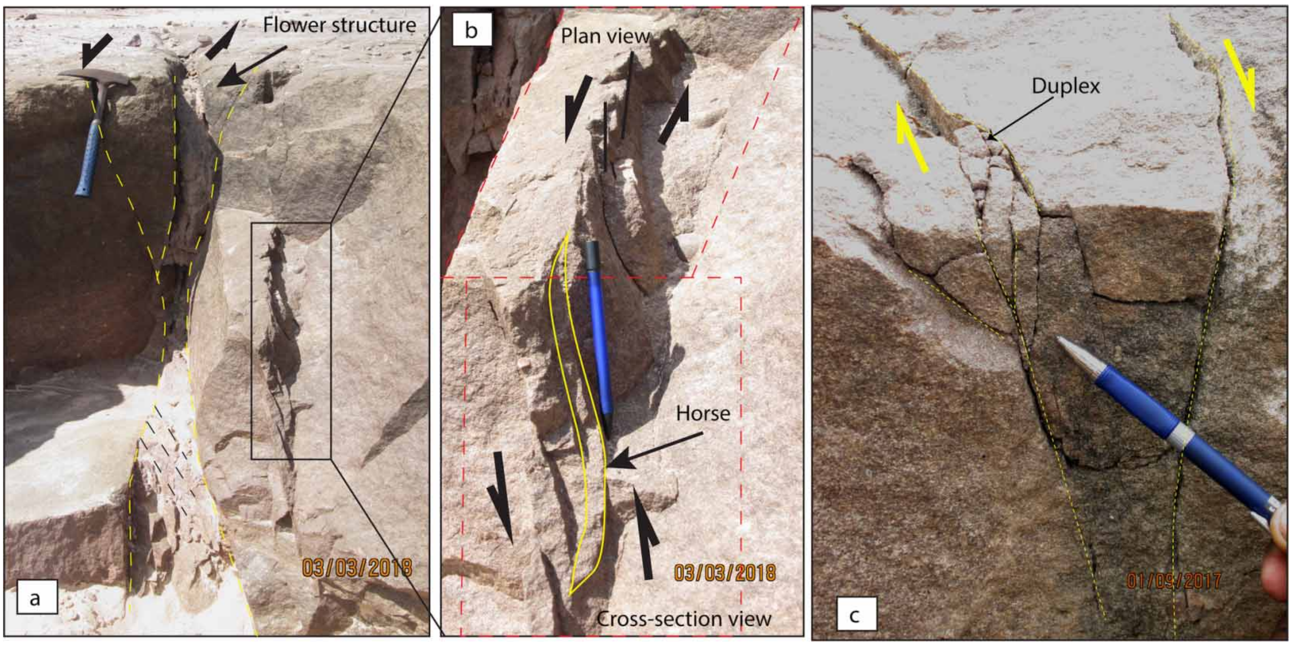


Figure 12. *Positive flower structures. (**a**) Positive hourglass flower structures along a sinistral fault (Z1) and (**b**) its well-developed horses in plan and cross-section view. (**c**) Positive flower structures along a dextral strike-slip fault (Z2) associated with a small duplex in plan view.*

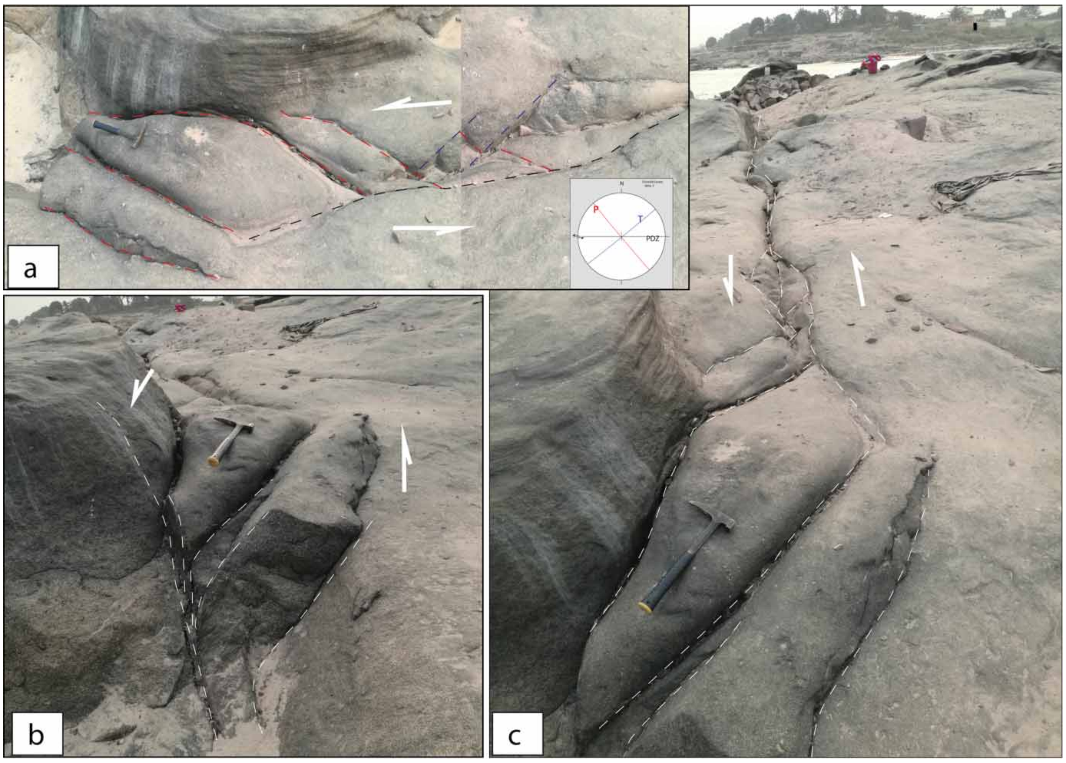


Figure 13. *Positive flower structures at fault tip in a sinistral fault (Z2). (**a**) and (**c**) Plan view geometry of the fault showing linking of P and T fractures, (**b**) positive flower structures associated with the convex-upward shape.*

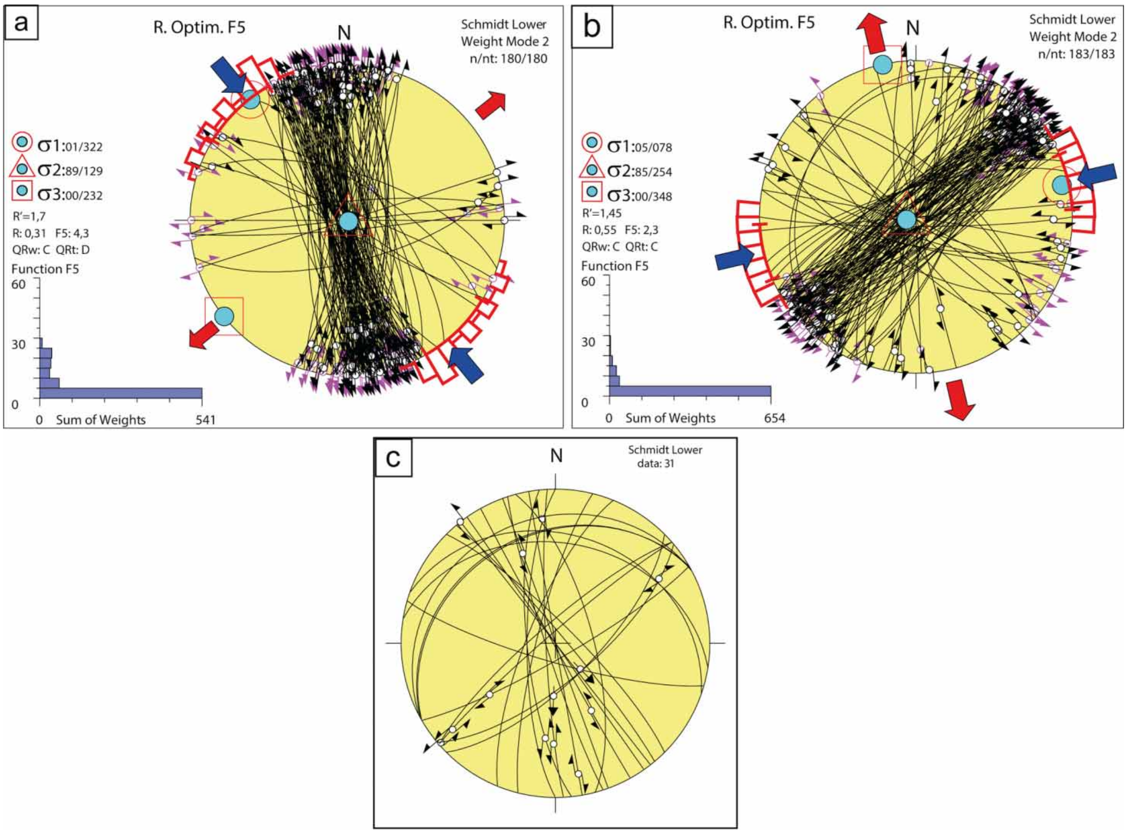


Figure 14. *Stress tensors of two phases of strike-slip deformation. (**a**) Stress regime obtained from northeast–southwest to north–south direction sinistral strike-slip faults. (**b**) Stress regime obtained from northeast–southwest oriented structures. (**c**) Rejected faults.*

marker, we used the type of bend and the pitch of the PDZ to infer the type of the flower structure. Releasing and restraining bends are associated with negative and positive flowers respectively in plan-view.

Branched fractures associated with an array of fractures observed in cross-section correspond to R shears or low-angle shear as noted by Naylor et al. (1986) in their Figure 11. At low inclination in plan-view, R-shears tend to become parallel to the direction of displacement and are referred to as Y-shears, (Bartlett et al., 1981). At the principal zone of deformation (PDZ), they are associated with extensional fractures in the field (Figures 9b and 10a). Yet, when low angle R-shears develop, lens connections are made through P-shears (Figure 11a, b and c) as noted by Naylor et al. (1986) in their experiments and by Woodcock and Fischer (1986) in their field and map analysis. In cross-section view, fractures that link an array of faults in flower structures (Figure 12a, at the bottom of the flower structures) can be considered as T-fractures or P (shear) fractures, depending on their kinematics. Naylor et al. (1986) also described them in their experiments (Figure 11d in Naylor et al., 1986). These types of fractures or linking fractures can be used to determine the strike-slip component at depth, as flower structures may show both normal dip-slip and reverse dip-slip in cross-sectional views.

Flower structure arrangement and fault damage zone classification (Kim et al., 2004)

Kim et al. (2004) suggest a remarkable and broad classification of strike-slip fault architecture in plan-view according to structures occurring at tips, wall, and linking damage zones. These arrangements match our field observations of flower structures occurring at each damage zone they described. Here, we suggest a conceptual model to represent our field descriptions. The classification of Kim and al. (2004) generally focuses on secondary developed structures in plan-view, but not the arrangement of flower structure along the fault trace. We synthesized our field observations to distinguish four types of flower structure arrangements in the Inkisi Group, which seem likely to depend on fault propagation and growth.

(i) Flower structures associated with wall damage zones: (Figures 15, 8 and 9a): they present in plan-view non-linked or linked parallel fault traces either by extensional fractures or contractional fractures between parallel fault traces. They were probably formed at the early stage of deformation by the interaction of fault segments at depth before their connection at the surface; in the field, some flower structures display loosely developed linking fractures between parallel faults with few displacements. Although they have been described in the experiments of Dooley and Schreurs (2012), they are also beautifully reported in 3D seismic analyses of intracratonic strike-slip faults occurring in the Tarim Basin of China (Deng et al., 2019, their Figures 12 and 13). The comparison of our small-scale structures with large-scale and seismic scale intracratonic strike-slip faults might appear to be unconventional, but strike-slip faults usually keep identical geometric features from the small scale to continental scale (Christie-Blick and Biddle, 1985; Kim et al., 2001)

(ii) Flower structures associated with linking damage zones: (Figures 15, 10 and 11a): such structures were most frequently identified in the field by previous studies (see review Cunningham and Mann, 2007). They present, in plan-view, a stepover linked either by extension fractures, contractional fractures, duplexes or lenses. They seem to be associated with an increase in deformation, when faults start linking at a relay zone. They are also likely to occur along high-displacement faults.

(iii) Flower structures associated with tip damage zones: these are quite rare in the literature, but some detailed evidence of their occurrence has been reported by Deng et al. (2019) in their Figure 14 and Figure 15. They seem to occur at tips in association with an increased rate of deformation.

(iv) "Hourglass" flower structures: (Figures 15, 9a and 12a): these structures are quite particular for the area of the study and seem to originate from a change of stress orientation with depth. As one plane changes its orientation with the PDZ, these flower structures would occur at the final stage of deformation. They have only been seen in linking and wall damage zones. The generation of these types of arrangements should be assessed in further detail.

Stress regimes and geodynamic significance

The presence of flower structures supports the evidence of strike-slip tectonic activity in the Inkisi Group. This corroborates other recent studies (Delvaux et al., 2017; Nkodia, 2017; Miyouna et al., 2018, 2020; Mees et al., 2019). The stress stage found in the first group (Z1), indicating northwest–southeast compression with the maximum horizontal compressive stress σ_1 322/01 (see Figure 14a), is well constrained with low uncertainties (006°). It is dominated by northwest–southeast sinistral faults conjugate to east–west dextral strike-slip faults and constitutes the first phase of deformation (D1) because the Z1 group faults are offset by Z2 (see Figure 5). The evident strike-slip tectonic activity for Z1 might be related to two geodynamic events having the same paleostress orientations:

- the propagation of stress from the southern subduction margin of Gondwana in the Permo-Triassic times, which formed the Cape Fold Belt (Catuneanu et al., 2005), and/or
- the compression in the Late Cretaceous to Eocene time that affected the intra-plate region of Africa during the opening of the south Atlantic ocean (Figure 16) (Guiraud et al., 1992, 2005; Basile et al., 2005).

This statement is supported by three major points. First, the Inkisi Group post-dates Pan-African tectonics (Tack et al., 2001, 2008; Callec et al., 2015; Linol et al., 2015; Affaton et al., 2016), and it is overlain by the Karoo units of Permian age in Angola (Oesterlen, 1980); therefore, causes of these deformations cannot be related to the Pan-African orogeny. Tack et al. (2008)

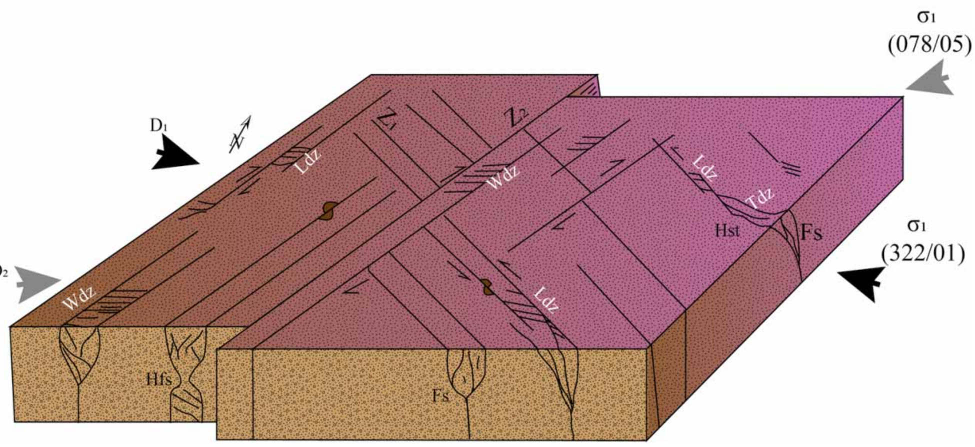
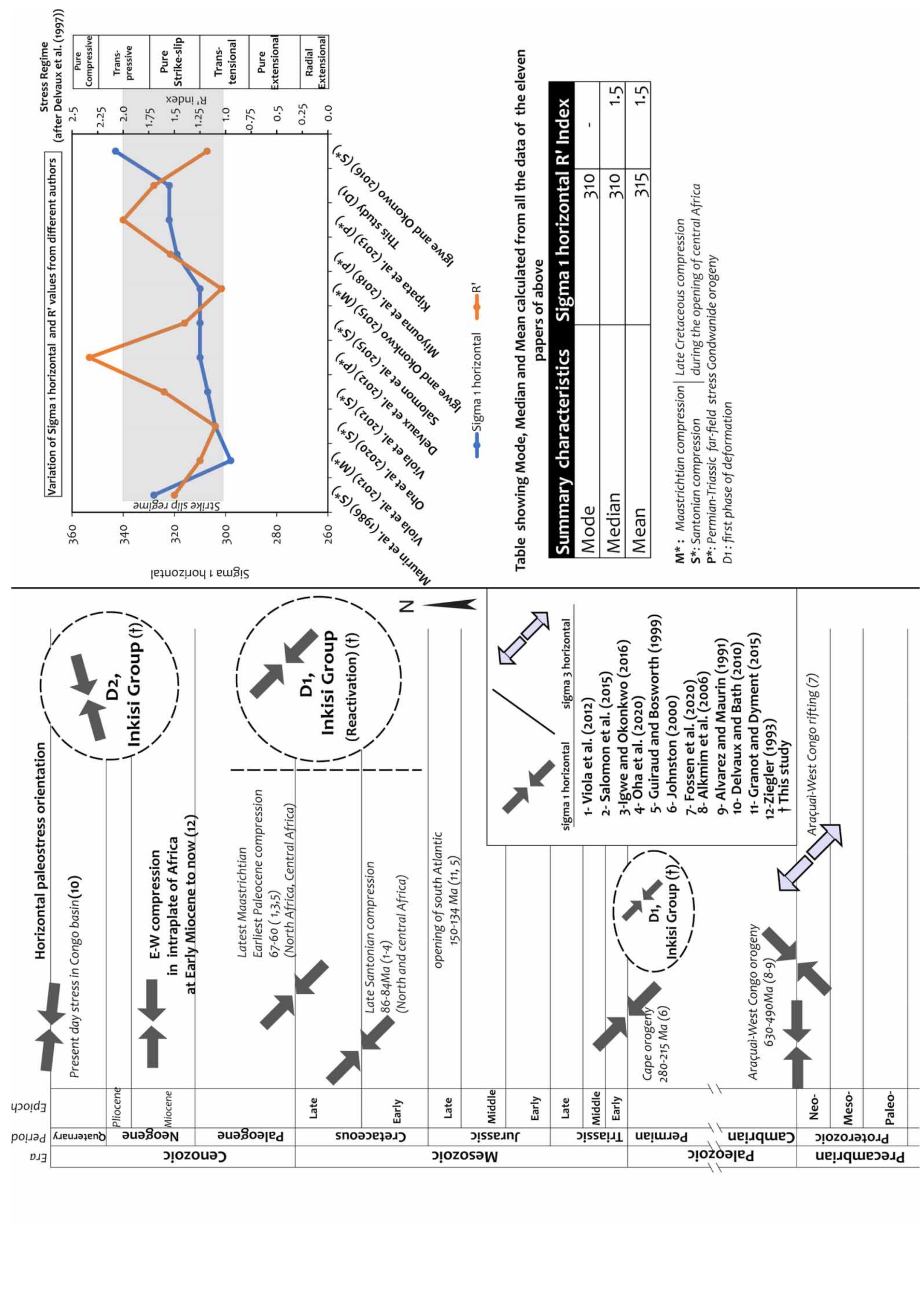


Figure 15. *Idealised model of different arrangements of flower structures along with strike-slip architecture, in-plan view and cross-section, in Inkisi Group. Wdz=wall-damage zone, Ldz=linking damage zone, Tdz=tip damage zone. Hfs=hourglass-flower structure, Fs=flower structure, Z1=first fault system, Z2=second fault system.*

suggested that the age of the Inkisi Group might be between early Paleozoic and pre-Karoo (320 Ma) (Catuneanu et al., 2005). Knowing that Karoo units have been deformed in most parts of Africa (De Wit and Ransome, 1992; Ring, 1995; Delvaux, 2001a; Catuneanu et al., 2005; Delvaux et al., 2012; Kipata et al., 2013), underlying units of the Inkisi Group might also be deformed. In the western branch of the African rift system in Tanzania, several rift basins developed in response to stress transmission from both the southern and the northern active margins of the Gondwana continent (Delvaux, 2001b; a). These rifts are aligned along the Tanganyika-Rukwa-Malawi (TRM) segment, which has recorded several tectonic (Delvaux et al., 2012) events from the Pan-African orogeny to present day. Delvaux et al. (2012), determined three stress stages in the TRM segment. The second stage, which followed the Pan-African (650 to 580 Ma), indicated a northwest–southeast compressive regime with a strike-slip component (Figure 16) quite similar to our first stage tensor. This tensor was obtained from the Lukuga Formation in the Namwele-Mkolomo coalfield, which comprises Karoo deposits of Permian age that are also described in the Congo basin (Fourmarier, 1914; Lepersonne, 1977; Cahen and Lepersonne, 1978; Kadima et al., 2011). The deformation of these Karoo deposits in the TRM zone has been related to the northwest–southeast compressive Gondwanide orogeny (Delvaux, 2001b; a; Delvaux et al., 2012) that took place at the southern margin of Gondwana in the Permo-Triassic (Johnston, 2000). This finding is also supported by apatite fission track thermochronology (Van der Beek et al., 1998), which indicates repeated phases of rapid cooling and denudation in the area during the Triassic (250 to 200 Ma). Even though the plunge of slickenlines of the second stress stage found by Delvaux et al. (2012) is much steeper than those found in this study, local perturbation of the stresses transmitted over 2500 km might have played a role in slightly changing the stress regime. The central Africa region might have reacted heterogeneously due to far-field stresses, as also proposed by others (Ziegler et al., 1995; Janssen et al., 1995). This statement confirms that the Gondwanide orogeny affected the Inkisi Group. The second point is that far-field stresses transferred from the southern subduction margin of Gondwana to the central part of Africa have also been reported (Daly et al., 1992; Tack et al., 2008; Kadima et al., 2011) within the overlying red bed units equivalent to the Inkisi Group in the Congo Basin. Daly et al. (1992) described positive flower structures and thrust faults interpreted from seismic profiles in the Congo Basin that were related to north–south compression from the Gondwanide orogeny. This effect of major contractional stress at a distance of 2500 km inland from the Gondwanide belts was tested by Trouw and De Wit (1999), who argued that internal pre-existing structures in the overriding plate during subduction may have eventually transmitted stress throughout the heartland of Gondwana. Thirdly, the opening of the south-central Atlantic Ocean in the early Cretaceous time (Granot and Dyment, 2015) was accommodated by numerous zones of intracontinental fractures and troughs in central Africa (Guiraud and Maurin, 1992; Maurin and Guiraud, 1993; Basile et al., 2005; Guiraud et al., 2005; Moulin et al., 2010; Heine et al., 2013b) and in northeastern Brazil (Fernandes and Amaral, 2002; Bezerra et al., 2014; Salomon et al., 2014, 2017) that underwent extension and compression within the African plate. The Benue trough in Nigeria, as well as the Dosa, the Dosé, and the Salamat trough in Chad, all underwent northwest–southeast to north-northwest–south-southeast compressive events in the Late Cretaceous that produced folds and strike-slip faults accompanied by positive and negative flower structures (Benkhelil, 1982; Guiraud et al., 1989; Genik, 1992). Paleostress reconstruction by Oha et al. (2020) in the Moku sub-basin of the Upper Benue Trough in Nigeria reported that this sub-basin developed under a northwest–southeast oriented strike-slip dominated transtension regime with σ_1 (304/34) in the Late Cretaceous. These results also confirmed the detailed paleostress reconstruction conducted by Igwe and Okonkwo (2016) in the southern part of the Benue Trough in Nigeria, which obtained a northwest–southeast to north-northwest–southeast oriented strike-slip extensional regime from Cenomanian to Maastrichtian



Summary characteristics	Sigma 1 horizontal	R' Index
Mode	310	-
Median	310	1.5
Mean	315	1.5

Figure 16. *Compilation of known compressive tectonic events that affected central Africa and surroundings and variation of sigma 1 and R' index values from different authors in comparison with our D_1 phase.*

(Late Cretaceous) dated faults and deposits. One may argue that plunge and azimuth of their sigma1 differs slightly in angle from our first stress stage. Nonetheless, most of the faults in the Benue trough show the same structural style as what we observed and are developed in a strike-slip tectonic setting. Preexisting structures might have played a huge control on local stress perturbations in the area, as several geotectonic features are located around the area. Additionally in Namaqualand in South Africa, Viola et al. (2012) identified two phases of compression, D7 (Santonian compression) and D9 (Maastrichtian compression) of a northwest–southeast oriented pure strike slip regime that they attributed to far-field effects of compression in central Africa during the opening of the Atlantic ocean in the Late Cretaceous. Their results were confirmed by Salomon et al. (2015) who found a similar oriented tensor from strike-slip faults. Most of the stresses and shortening axes found in the Benue trough show northwest–southeast (155°) strike-slip related deformation associated with transtension zones and transpression zones (Benkhelil, 1982, 1986, 1989; Guiraud et al., 1989; Benkhelil et al., 1998). This structural style is very similar to our tensor. Subduction on the southern margin of Gondwana in the Permo-Triassic had a similar orientation to compressional events in the Late Cretaceous; therefore, their separation in the field would be challenging to assess. Only absolute dating of different fault systems can provide an efficient separation. The Late Cretaceous compressive stress would have created a larger impact than the subduction at the southern margin of Gondwana if we consider the distance from where the stress initiated.

The second stress stage found for the Group Z2 corresponds to the second phase of deformation (D2). It shows east–west compression as the faults of Group Z2 offset the faults of Group Z1 (Figure 5). This stage is considered the latest, with the maximum horizontal compressive stress σ_1 078/05 well constrained (see Figure 14b). The phase D2 shows dominantly northeast–southwest dextral strike-slip faults conjugate to east–west sinistral strike-slip faults. The second stage would be related to the propagation of intra-plate compressive east–west stress occurring after the opening of the South Atlantic Ocean in the Miocene. This is supported by the fact that a major east–west compressional phase started to build up during the Miocene (Ziegler, 1993; Guiraud et al., 2005) after the opening of the south Atlantic ocean, along with the propagation of ridge push. This stress propagation may still have an ongoing effect in central Africa according to the hypothesis by Wiens and Stein (1983, 1985). These authors demonstrated that oceanic lithosphere is subjected to strike-slip or thrust compression in the spreading direction between 50 and 100 Ma after the initiation of the spreading ridge. The central Atlantic might have recorded intraplate stress in the continent from the Paleocene until present time. Additionally, focal mechanism data (Delvaux and Bath, 2010) obtained within the Congo river region give a compressive regime oriented east–west for the present-day stress (Figure 16). This implies that the second tensor would have operated since Miocene time and may continue until present-day. In Cameroon, the Central African shear zone (CASZ) strikes northeast and has recorded several earthquakes (Dorbath et al., 1986; Ateba et al., 1992) that were attributed to the ridge effect of the central Atlantic. Ngatchou et al. (2018) also found that earthquakes in south Cameroon are generated along the dextral Central African Shear zone in central Africa. They also reported an east–west compression from these earthquakes that is similar in orientation to the second fault system. Global positioning system networks confirm that active deformation is taking place far from plate boundaries (England, 1987). Thus, the second stage coincides with east–west compression resulting from the ridge push effect.

Conclusions

Primary conclusions from this study are as follows:

- The Inkisi Group has been affected by at least two phases of strike-slip deformation that engendered two strike slip fault systems. The first system shows north-northwest–south-southeast striking sinistral strike-slip faults and minor east–west striking dextral strike-slip faults. The second system is constituted of dominant northeast–southwest striking dextral strike-slip faults and minor northwest–southeast striking sinistral strike-slip faults. The first system of faults resulted from a northwest–southeast oriented pure strike slip regime with σ_1 322/01, while the second system of faults resulted from east–west oriented pure strike slip faulting with σ_1 078/05.
- The first phase of deformation coincides with two geodynamic events of equal northwest–southeast orientation (σ_1 322/01): the southern subduction margin of Gondwana at the Permo-Triassic, and compression in the Late Cretaceous to Eocene that affected the intra-plate of Africa during the opening of the south Atlantic Ocean. The second phase of deformation is due to the propagation of intra-plate compressive east–west (σ_1 078/05) stresses during the opening of the South Atlantic Ocean related to ridge push, which started to build up in the continent during Miocene times and continues to present.
- Both phases of deformation developed several secondary structures. Flower structures are present in four types of arrangement in the Inkisi Group, which seem likely to depend on fault propagation growth and damage zones: *(i) Flower structures associated with wall damage zones; (ii) Flower structures associated with linking damage zones*; *(iii) Flower structures associated at tip damage zones;* and *(iv) "hourglass" flower structures.*

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