Seismogenic Fault Reactivation in Western Central Africa: Insights from Regional Stress Analyses

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Key Points:

- A transpressive regime with NNE-SSW horizontal maximum compressive stress controls intraplate seismicity in Western Central Africa
- Regional stresses acting on offshore oceanic fracture zones are compatible with those acting along the onshore continental margin.
- Favorable orientation and hydrothermal alteration of onshore preexisting Archean - Cenozoic faults make them susceptible for reactivation.

Abstract

The onshore continental margins of western Central Africa have been hosting potentially damaging earthquake events for decades; yet, the links between the seismicity, the contemporary stress field, and pre-existing faults are not well understood. Here, we analyze the regional stress fields along the coastal margin and interior cratonic areas using earthquake focal mechanisms, map and characterize the detailed structure of preexisting fault systems in outcrops, and asses the reactivation potential of the mapped structures. Our results show that the earthquakes originate under a transpressive stress regime with a horizontal maximum principal compressive stress ($\sigma 1$) that is oriented NNE-SSW. We show that regional stresses acting on offshore oceanic fracture zones are compatible with those acting along the onshore areas of the continental margin. Field observations reveal the presence of large fault systems that deform both the Precambrian basement and Phanerozoic sedimentary sequences, with widespread hydrothermal alterations of calcite veining, quartz veining, and palygorskite mineralization along the fault zones. Along the margin, the preexisting NNE-, NNW-, and N-S -trending strike-slip faults and normal faults show a high slip tendency (60 – 100 %), whereas in the cratonic interior, the NW- and N-S -trending thrust faults are the most likely to reactivate. We argue that favorable orientation of the preexisting faults and potentially, their hydrothermal alteration products, define the susceptibility of the faults to seismic reactivation. We propose that possible stress propagation into the near-shore and onshore tip zones of oceanic fracture zones may be driving stress loading on pre-stressed fault systems onshore.

Keywords: Earthquakes, Intraplate seismicity; Slip tendency; faults; Western Central Africa; focal mechanism.

Plain Language Summary

We investigated the stresses that are generating earthquakes and the compatibility with preexisting fault systems along the stable continental margin of Western Central Africa. The stresses acting on the continent interior were also determined and distinguished. We found that the regional stresses acting on offshore oceanic fracture zones are compatible with those acting along the onshore areas of the continental margin. In this stress field, the potential for reactivation of the observable preexisting onshore fault systems is very high, particularly for those oriented NNE-SSW and N-S. We propose that the stresses along transform faults and oceanic fracture zones may propagate into near-shore and onshore areas, leading to earthquakes on the preexisting faults.

1 Introduction

Earthquakes remain one of the most catastrophic natural hazards in human history. Beyond the associated fatalities, earthquakes also leave behind lasting environmental and economic crises in the affected communities. Although, the largest magnitude earthquakes have been recorded along plate boundaries (McCaffrey, 2008) associated with plate subduction, collision, and continental rifting, several large magnitude (Mw>6) events have also been recorded in intraplate regions (e.g.,Talwani, 2014; Tuttle et al., 2002), and more intriguingly, along passive continental rift margins where the sources and occurrence of earthquakes remain less understood. Among the large magnitude and devasting earthquakes recorded in continental intraplate regions previously thought to be relatively stable include the Mw 6.2 Latur Earthquake of September 29, 1993 in South India which claimed a death toll of 11,000 (Gupta et al., 1998) and the Mw 6.2 Guinea earthquake of December 22, 1983 which caused 1500 fatalities and significant property damage (Musson, 1992; Suleiman et al., 1993). On the causes of intraplate seismicity, proposed hypotheses include the reactivation of preexisting structures (e.g., Calais et al., 2016; F. Kolawole et al., 2019; Folarin Kolawole et al., 2017; Ngatchou et al., 2018) driven by far-field stress transmission from active plate boundaries (Delvaux et al., 2016; Delvaux & Bath, 2010; Nkodia et al., 2020; Wiens & Stein, 1983, 1985), gravitational body forces (Levandowski et al., 2017), deglaciation-related isostatic rebound (Lund Snee & Zoback, 2020), underground industrial activities(Grigoli et al., 2017; Keranen & Weingarten, 2018) , and thermal weakening of the lithosphere (Holford et al., 2011).
Some passive rifted margins across the world are known host pronounced distributed seismicity, among which are well-instrumented regions such as the eastern Brazilian Atlantic margin (Assumpção, 1998), the southern Australian margin (Holford et al., 2011), and the eastern North American margin(Sbar & Sykes, 1973; Zoback, 1992). However, in poorly instrumented regions, such as Equatorial West Africa and western Central Africa where widespread seismicity is becoming increasingly prominent, the relation between the present-day stress regime acting in these regions, the sources of stress perturbation, and the mechanics of reactivation of inherited structures are not known (Olugboji et al., 2021) . This knowledge gap hinders the development of viable early-warning mechanisms for hazard mitigations in local communities located in such regions.
In this study, we explore the passive margin of Western Central Africa, an area which exemplifies considerable intraplate seismicity in both its offshore domains and within the continent (Figs. 2a-b). This region has been the subject of much research for almost a century (Krenkel, 1923; Junner and Bates, 1941; Blundell, 1976; Burke, 1976; Bacon and Quaah, 1981; Ambraseys and Adams, 1986; Yarwood and Doser, 1990; Onuoha and Ezeh, 1992a; Musson, 1992; Suleiman et al., 1993; Delvaux and Bath, 2010; Amponsah et al., 2012; Kutu, 2013; Nwankwoala and Orji, 2018; Meghraoui et al., 2019; Oladejo et al., 2020; Olugboji et al., 2021; Kadiri and Kijko, 2021). Although most of the studies focused on the use of remote sensing to provide a seismotectonic model for the region (Adepelumi et al., 2008; M. O. Awoyemi et al., 2017; M. Awoyemi & Onyedim, 2004; Bouka Biona & Sounga, 2001; Oladejo et al., 2020), the characterization of the structures is sparse, and there remains a limited understanding of the detailed structure and current stress state of the potentially-seismogenic preexisting faults.

The aim of this contribution is to evaluate the possible current regional stress regime that is most dominant and is responsible for reactivating preexisting structures along the western Central African passive margin by using the slip tendency analytical techniques. By determining which types of structures that are being reactivated within the study area and the associated kinematics, we provide some insight into the seismic hazards and possible drivers of widespread seismicity along the margin. We suggest that the results of this study are relevant for building a realistic model for seismic hazards and the associated coseismic ground motions for this region and similar poorly-instrumented passive margin environments:

2 Geological and Tectonic Setting

2.1 Regional Geology of Western Africa and Continental Margin

The Western Africa continental region is mainly dominated by Archaean basement, overlain by Neoproterozoic and Phanerozoic units (Fig. 1). The Archean rocks are hosted within the Congo Craton in the western Central Africa region and in the West African Craton in the far northwestern sub-region. These cratons are separated into several blocks limited by Neoproterozoic and Paleoproterozoic terranes and shear zones, interspersed by sedimentary basins (Fig. 1). The 3.1 - 2.7 Ga Congo Craton (Thiéblemont et al., 2009; Turnbull et al., 2021) is subdivided into five blocks: (i) the Ntem-Chaillu block in the central and northwestern domains, covering the region of Cameroon, Gabon, and Republic of Congo (Kessi, 1992; Tchameni et al., 2000; Gatsé Ebotehouna et al., 2021a); (ii) the 2.5 Ga Angola block to the south in Angola (De Carvalho et al., 2000; Jelsma et al., 2018); (iii) the 3.6 - 2.5 Ga Kassaï block to the southeast in DRC (Batumike et al., 2006); (iv) the 3.2 - 2.5 Ga NE-Congo Block in the Northern DRC (Turnbull et al., 2021), and (v) the 2.8 - 2.6 Ga Tanzanian block.

These cratonic blocks have accommodated multiple episodes of large-scale brittle deformation which emplaced large discontinuities within them. Akame et al., (2020, 2021) documented the presence of large NW-SE, NE-SW and E-W trending brittle and ductile shear zones in the Ntem-Chaillu Block, inherited from Neoarchean orogenesis. Similar deformation were also reported in the laterally equivalent Souanké Archean rocks in the Ivindo region of Republic of Congo (Loemba et al., 2022) In the Souanké domain, the brittle shear zones show evidence of reactivation into normal faulting kinematics interpreted to be related the Cretaceous opening of Atlantic Ocean (Loemba et al., 2022).The Ntem-Chaillu block is bounded to the north by the Oubanguides Belt which developed during the Pan-African Orogeny (550 ±100 Ma) and was subsequently deformed in the Mesozoic by the continental-scale, NE-trending Central African Shear Zone (CASZ; Fig. 1). The CASZ, which extends into the Borborema province of NE Brazil (Miranda et al., 2020), is considered to be an accommodation zone that was activated during the opening of the South Atlantic (Moulin et al., 2010; V. Ngako et al., 2003; Vincent Ngako et al., 1991; Njonfang et al., 2008; Wilson, 1965). Recent earthquakes and associated source mechanisms along a segment of the CASZ (e.g., 2005 Montalé, Cameroon earthquake) suggests that the CASZ structure may still be active as the Atlantic Ocean basin continues to open (Ngatchou et al., 2018).
Along the western margin of the Congo Craton, the Ntem-Chaillu and Angola cratonic blocks are separated by the Pan-African West-Congo Belt (630 Ma – 490 Ma) the western part of which was later rifted during the opening of the Atlantic Ocean (Alvarez & Maurin, 1991; Boudzoumou & Trompette, 1988; Bouenitela, 2019; Fullgraf et al., 2015; Hossié, 1980). The fold-thrust terranes of the West-Congo Belt is noted to host large (>90 km-long) NE-SW, NW-SW and N-S trending brittle shear zones (Alvarez & Maurin, 1991; Nkodia et al., 2021). In the Republic of Congo (RC), Democratic Republic of Congo (DRC), and Angola, the terranes of the mobile belt are covered by Ordovician-Silurian sandstones which record phases of strike-slip deformation, first during the Gondwanide Orogeny in the Permo-Triassic, then during Cretaceous opening of the Atlantic

(Miyouna et al., 2018; Nkodia et al., 2020). The Late Paleozoic sandstones of the Inkisi Group show reactivated and segmented strike-slip faults zones oriented NW-SE, NE-SW, and E-W, observable in field outcrops (Miyouna et al., 2018; Nkodia et al., 2020a) and in seismic reflection images (Damien Delvaux et al., 2021; Kadima et al., 2011). The phases of Late Paleozoic-Early Mesozoic contractional tectonic deformation in the Congo Basin are observable across eastern and southern Africa (Delvaux et al., 2021) However, there is evidence for the presence of through-going structures which deform both the Paleozoic-Mesozoic and Cenozoic sedimentary sequences (Damien Delvaux et al., 2021; Kadima et al., 2011), suggesting there might be still be on-going intra-continental tectonic deformation in Central Africa. Mbéri Kongo (2018) showed that the Paleogene sand deposits of the Bateké Plateau, Congo Basin, have been deformed by large strike-slip faults with associated conjugate normal faults. Northwest of the Oubanguides Belt, in West Africa, the Cretaceous intracratonic Benue Rift developed within the Trans-Sahara Mobile Belt as a corridor of transtensive faults with associated magmatism (Ajakaiye et al., 1986; Benkhelil, 1989; Oha et al., 2020). The closure and failure of the rift occurred in the Santonian, associated with a transpressional deformation of its Cretaceous syn-rift deposits (Ofoegbu, 1985; Benkhelil, 1989). The Trans-Sahara Mobile Belt host several N- to NNE-trending shear zones associated with the Proterozoic amalgamation of West Gondwana. Some of the shear zones also record evidence of brittle deformation during the opening of the Atlantic Ocean, an example of which is the Kandi fault zone which served as an accommodation zone during the rifting event (Affaton et al., 1991).

Figure 1: *Map of the bedrock geology of the Nubian Plate showing major litho-tectonic subdivisions of the crust. Dwc1, Dk, Dbk, Dngov, Dso represent field sites where structural measurements of fault systems were collected. Dwc1 represent the study site of a thrust fault system in western Congo. Dwc2 is a combination of strike-slip faults along Dk and Dngov which represent field sites in Kolas Quarry, Republic of Congo, and Ngovo Cave, Democratic Republic of Congo respectively. Dbk represents the field study sites of fault systems in Brazzaville and Kinshasa areas. AFZ: Akwapim Fault Zone, BFZ: Bouandary Fault Zone, CASZ: Central African shear zone.*

2.2 Oceanic Fracture Zones in the Gulf of Guinea, Western Nubian Plate

The oceanic crust of the Atlantic Basin dominates the western portion of the Nubian Plate and hosts several fracture zones that extend eastward from the active transform faults at the Mid-Atlantic Ridge plate boundary towards western Africa's rifted continental margin (Fig. 1). Oceanic transform faults developed within the oceanic crust starting sometime after continental break-up and serve to accommodate the lateral movement of tectonic plates, and lateral variation of spreading rates, and to facilitate connectivity between ridges and trenches (De Long et al., 1977, p. 199; Gerya, 2012; Hensen et al., 2019). Due to their strong topographic expression at the sea floor , their structural and geochemical alteration of the oceanic crust, and temporal accretion patterns, transform faults and oceanic fracture zones are mappable in bathymetric, seismic reflection, gravity, and magnetic datasets (Delteil et al., 1974; Fail et al., 1970; Gorini & Bryan, 1976; Guiraud et al., 2010; Mascle & Sibuet, 1974).

Although the active plate boundary (i.e., spreading oceanic ridges and subduction zones) host most of the seismicity of oceanic basins, oceanic fracture zones and their flanking areas also accommodate significant seismic activity and represent seismic hazards within intraplate areas away from the plate boundaries (Fig.2a; Burke, 1969; Lay, 2019; Okal & Stewart, 1982). On the lateral growth of oceanic fracture zones, Burke et al. (1969) proposed a mechanism of propagation towards the continents by extension fracture mode which produce stress transmission that initiate seismic failure at the continental margins. In the Atlantic Ocean, some of the most active fracture zones which commonly extend close to- or into the western Africa rifted continental margin include Romanche, Chain, Charcot, Ascension, and Saint Paul fracture zones (Figs. 2a-b; Heezen et al., 1964, 1965; Mascle & Sibuet, 1974). A few studies argue for the lateral continue of oceanic fracture zones onto the continent of West Africa and causative relationship with onshore earthquakes based on: 1) the alignment of on-shore magnetic lineaments in Nigeria with the trends of the offshore fracture zones (Ajakaiye et al., 1986), and 2) the colocation and alignment of rifted transform margins such as the Ghanian and Ivorian coastline with the Romanche and St Paul fracture zones respectively (Fig. 2a; Antobreh et al., 2009), and 3) recent (<10 million years) acceleration of strain rates on oceanic transform faults post-continental break-up in the Late Cretaceous (Meghraoui et al., 2019). However, questions remain on the link between the current stress regime acting on the margin of western African continent and the mechanisms and triggers of seismic reactivation of preexisting structures.

3 Data and Methods

3.1 Earthquake Data

The study area covers the region between latitudes 16.70°N and 14.07°S, and longitudes 23°W and 24.66°E. For this region, we built a database of earthquakes and their related focal mechanism data from publicly-accessible global catalogues which includes the International Seismic Center (ISC), the United States Geological Survey (USGS), the Global Centroid-Moment-Tensor (CMT), and the GFZ GEOFON earthquake catalogs.

3.2 Mapping of Tectonic Lineaments

In order to delineate mega-scale tectonic structures in the oceanic crust and around the onshore continental coastal margin, we utilized hillshade digital elevation model (DEM) maps generated from bathymetric and topographic data. In the offshore areas, we delineated and mapped the traces of oceanic fracture zones on DEM of bathymetric data extracted from GEBCO (GEBCO Bathymetric Compilation Group 2021, 2021), which has a spatial resolution of 1 arc minute (~1.5 km). Within the onshore continental areas, using previously published geologic maps and field observation where possible (see details in section 3.3) as constraints, we manually interpreted and digitized visible structural lineaments defined by steep laterally-continuous topographic relief gradients from a mosaic of scenes of a 30 m resolution ALOS-type radar interferometric digital elevation model (DEM) images, following a standard approach (Burbank & Anderson, 2011). The ALOS data was obtained from the ALOS Global Digital Surface Model (https://www.eorc.jaxa.jp/ALOS/en/aw3d30/data/index.htm). The previously published geologic map that guided the lineament interpretation is the tectonic map of Africa by Milesi et al. (2010) in which the faults were compiled from field studies and gravity anomalies, conducted by geological surveys groups of different countries.

3.3 Field Observations and Collection of Structural Measurements

In the onshore areas of the Republic of Congo (R.C) and Democratic Republic of Congo (D.R.C), we conducted field observations and collection of structural data along the fault and fracture systems in outcrops. This field campaign also served as ground-truthing to constrain the mapping of structural lineaments in hillshade maps. The field campaigns were conducted in the regions of Brazzaville, Dolisie, and Souanké regions of R.C, and in the Kongo Central region of D.R.C. The fieldwork helped to confirm the geologic origin of some of the interpreted lineaments as fault strands or brittle shear zones where they are accessible. In the field outcrops of the faults and brittle shear zones, we collected measurements of strike and dip of fault planes, trend and plunge of slip vectors (striations) along the surfaces, and we documented evidence and characteristics of geochemical alterations of the fault zones. We have provided information on our field measurements in the supplementary file of this manuscript. The structural field measurements provide fault plane orientation data that we used as one of the inputs into the slip tendency analysis (see section 3.4).

3.4 Assessment of Contemporary Stress Field and Slip Tendency of the Preexisting Structures

Following a standard approach, we used the Win-Tensor program (D. Delvaux, 2012) to determine the current stress field acting on the Gulf of Guinea section of the Nubian Plate, using the information on source parameters of earthquake focal mechanism solutions as input data. The focal mechanism solution data were compiled from several literature review (see supplementary files), Global CMT moment tensor, and GFZ GEOFON earthquake catalogs (Fig. 2b). In cases where the focal mechanism solution of the same earthquake event is produced by multiple earthquake databases, we considered all the solutions in order to guarantee the precision of the resulting stress tensor solutions. For our analysis, since the available focal mechanism solutions are sparse across the region and the seismicity is distributed across 1) offshore and onshore areas along the coastal margin corresponding to a rifted tectonic domain and the underlying pre-rift Proterozoic mobile belt, and 2) an Archean cratonic interior that has experienced failed rifting and inversion, we divided the study region into three sub-regions defined by three boxes (sub-regional Boxes 1, 2, and 3 in Fig. 3b). The division was made by considering the assumption that each box has a uniform stress. Two boxes cover the coastal margin areas: one along the Gabon-Cameroon and the other along the Ghanian coastal margins; whereas the third box covers the cratonic continental interior of central Africa.

The Win-Tensor program uses the stress inversion method (Angelier, 1975, 1989; Angelier & Mechler, 1977) to determine a reduced tensor which contains the orientations of the principal compressive stress axes ($\sigma 1$, $\sigma 2$, and $\sigma 3$) and the stress ratio, R. The program first estimates the tensor solution using the determination of PBT (compression, intermediate and tensional) axes method and the Right Dihedron method. This initial stress tensor solution serves as a starting point to determine a more constrained tensor solution using an iterative Rotational Optimization method. The latter method uses a misfit function that minimizes the difference between the calculated slip direction and the resolved direction. Fault planes that show large misfit angle are rejected in order to have a better constrained result. The stress index regime, R', typified the regime associated with the solution tensor. R’ is an improved R ratio that gives the type of stress regime in a continuous scale of 0 to 3 (Fig. 2).

Figure 2: *Standard values of the stress index R' with respect to the stress regime (modified from Delvaux et al., 2017).*

The resultant tensor solutions from Box 1 and Box 2 were applied on the mapped fault systems in central Africa to determine the slip tendency of the different observed fault plane geometries. Note that we do not use the tensor solution for Box 3 because it is similar to that of Box 1 (see section 4.3). Slip tendency quantifies the potential for reactivation of fault planes under a given stress field (Morris et al., 1996). The magnitude of slip tendency depends on the ratio of shear stress to normal stress resolved on a fault or fracture surface, and the frictional characteristic of the rocks. The Win-Tensor program determines a normalized slip tendency (Tsn) (Lisle & Srivastava, 2004) rendered as continuous values in a colored scale of 0 to 1. The planes with a slip tendency above 0.6 are considered to have a high likelihood to be reactivated, and less likely are the planes below 0.6. For our analysis, we use 0.3 as the coefficient of friction according to the work of Angelier (1989). We assume a cohesionless residual strength envelope for the faults, defined by 0 MPa cohesion, based on the outcrop observation of widespread brittle reactivation of hydrothermally-altered fault zones (see section 4.2).

4 Results

4.1 Spatial Distribution of Earthquakes and Mapped Tectonic Lineaments

Offshore, seismic events are either collocated with or occur in the vicinity of traces of oceanic fracture zones which show dominant trends of ENE and NE (Fig. 3a). Some events also occur along the Cameroon volcanic line and around the Bi**é** Dome in Angola. However, onshore, along the coastal margin and continental interior areas, the regional seismicity patterns show clustering of events that are collocated with or in vicinity of the mapped tectonic lineaments (Fig. 3a). For example, at the location of field site Dso, the epicenter of a Mw 6 event is collocated with the trace of a large ENE-to-NE trending fault system in the Ntem-Chaillu Block (see lineament with label 'Dso' in Figs. 1 and 3a). More interestingly, earthquakes cluster at the location where the Romanche Fracture Zone extends onto the Ghanian shoreline (Fig. 3a); and at least one of each of the nodal planes on the associated focal mechanism solutions show a trend that is parallel or sub-parallel to the fracture zone orientation (Fig. 3b). In southern Ghana and surrounding regions, tectonic lineaments show dominant sets trending NNE and ENE of which the latter is parallel to the trend of the Romanche Fracture Zone (Fig. 3a). Most of the focal mechanism solutions of the earthquakes (Fig. 3b) show a dominance of thrust fault and strike-slip fault regime. Only 10 % of events show normal faulting regimes (pie chart in Fig. 3b) and most are restricted to the rifted costal margin. Within the continental interior, the strike-slip and reverse faulting regime appear to be distributed across a broad region.

Figure 3: *(a) Relief map showing the distribution of earthquakes in the Western Africa passive margin. AFZ, CASZ are the Akwapim Fault zone, the Central Africa shear zone. (b) Focal mechanism solutions for earthquakes in the western part of the Nubia Plate, obtained from several literature review, Global CMT moment tensor, and GFZ GEOFON earthquake catalogs. The boxes show the area where conducted stress inversion on focal mechanism results. The pie-chart show the frequency distribution of the different tectonic regime acting on the area. TS: trenstensional regime; NF: normal faulting regime; SS: strike-slip faulting regime; TF: thrust faulting regime.*

4.2 ***Fault Structure in the Field Outcrops***

The study area is dominantly affected by strike-slip faults trending NW-SE, NE-SW, and minor ENE-WSW to E-W. Locally, these regions showed thrust faults and normal faults settled during Pan-African orogenies, post-Pan-African and the opening of Atlantic Ocean. At the field sites in Republic of Congo (RC) and Democratic Republic of Congo (DRC), observable deformation in the Paleozoic sandstones of the Inkisi Group mostly showed steep strike-slip faults and joints. Almost all strike-slip faults are arranged in relay segments or in a corridor of segments connected by extension fractures (Figs. 4a, 4d). Their traces attain 400 m in length in the outcrops, but their corresponding lineaments mapped in regional-scale DEM hillshade maps reach 80 - 90 km. In quarries, cross-sectional views of the fault-fracture systems show exposures of up to 50 m in height.

The fold-thrust terrane of the West Congo Belt is composed of two domains with distinct structural styles. One of the domains is dominated by major NW-trending low- to high-angle thrusts which control the NE vergence of the belt, and their associated high-angle back-thrusts (Fig. 4b). This structural style primarily affected schistose rocks with intruded dolerite, diamictites, quartzites, and sandstones units. The other domain is marked by a basin structure, a synclinorium, that rest on thrust sheets within the orogenic belt. This basin is dominated by carbonate sequences which are cut by major NE-trending strike-slip brittle shear zones (Fig. 4e). The strike-slip shear zones are arranged in step-overs associated with én-echelon extension fractures or normal faults. These faulting styles are observable down to 200 m depths in the caves of Ngovo and Ndimba. In northern RC, Archean rocks of Souanké host 2.8 Ga charnokites, gneisses, and pegmatites which are also deformed by the brittle shear zones. Nearly all the brittle shear zones observed on the field show linking architecture with relay zones connected either by extension fractures or duplex structures (Fig. 4c). On a slip surface along the strike-slip faults, we find evidence of over-printing of sub-horizontal slickenlines by vertical slicklines (Fig. 4f), indicating that these NE-SW, WNW-ESE, NW-SE and N-S trending strike-slip faults have been reactivated in dip slip.

Figure 4: *Field observations of faults systems. (a & d) Fault systems in outcrops of the Inkisi Group (Dbk), showing fracture patterns (highlighted in white dashed line in 3a), and a fault zone showing segmented faults in a duplex zone (in 3d), at the Kombé quarry, located near the Congo River, Brazzaville. (b & e) Faults systems (Dwc1 & Dk) in the West-Congo Belt showing successively thrust and back-thrust affecting schists and quarzites, in Dolisie along the RN1 primary road, and strike-slip fault planes in Kolas quarry near Loutété region. (c & f) Faults systems (Dso) in Souanké showing high-angle planes of strike-slip faults in the area (in 3c) and, a NE-trending plane that shows horizontal striae that is over-printed by vertical striae associated with calcite fibers, indicating a later normal faulting reactivation of the strike-slip faults. The dashed lines in Fig. 3f represent the directions of striae.*

In addition to the observed brittle deformation along the fault systems, we also note a widespread occurrence of geochemical alterations along the fault zones. For example, at field sites Dwc1 and Dk located in the West Congo Belt, several strike-slip fault zones show calcite mineralization that occur in accretion steps (Figs. 5a-c), and a few other fault zones show iron staining along the fault planes (Fig. 5b,c,d). Likewise, in the fault zones hosted in schistose terranes (e.g., Dk and Dngov), we observe networks of quartz veins injected along thrust faults and shear zones (Fig. 5f). In the sedimentary sequences (Inkisi Group; location Dbk), the fault zones are either mineralized by palygorskite, calcite, or a mix of both (Fig. 5e). However, at all the field sites visited, we commonly observed brittle reactivation of the mineralized fault and fracture planes evidenced by sheared mineral fibers with characteristic chatter marks, or tensile fracturing of the mineralized zones.

Figure 5: *Geochemical alterations along mineralized fault surfaces. (a) Accretion calcite steps along NW-SE strike-slip faults in carbonates rocks of the West Congo Belt, DRC. (b - c) Carbonate-hosted faults surfaces covered by accretion calcite steps and iron staining. Note that the carbonate rock in Figure 5b has penetrative cross-bedding structures that should not be confused with slickenlines. (d) Fault surface in Inkisi sandstones associated with iron alteration realm. (e) Slickensided palygorskite along a fault in Dbk fault system. (f) Deformed doleritic intrusion along a high-angle thrust fault (230/40) injected with quartz veins in the Dwc1 faults system.*

4.3 Contemporary Stress Fields within the Analyzed Sub-Regions

All three sub-regional boxes show a compressional strike-slip (i.e., transpressive) stress regime with a maximum horizontal compressive stress (SHmax) orientation that lies in the NE-SW quadrant (Fig. 6). The quality of tensor solutions is of B type, indicating that they are well-constrained. The standard deviation of the Shmax is less than ±15° for all the boxes, as Box 1, 2, and 3 show Shmax standard deviations of ±5.7, ±11.1, and ±14.3 respectively. The nodal planes of all tensors are in reactivated positions in the Mohr diagram (Figs. 6c, d, f). However, unlike the Box 2 where SHmax is oriented NE-SW (051° trend, 30° plunge), boxes 1 and 3 are more similar in that they show an Shmax orientations of NNE-SSW (014° trend, 4° plunge) and N-S (184° trend, 3° plunge) respectively. In a transpressive stress regime, the SHmax corresponds to the maximum principal compressive stress ($\sigma 1$).

Both Boxes 1 and 3 show strike-slip nodal planes that are oriented NW-SE and NE-SW (Figs. 6b, 6b-e); however, Box 1 has events with E-W trending sinistral and high-angle N-S trending normal nodal planes, and in Box 3, some of the events show conjugate reverse faulting patterns with nodal planes trending NW-SE and ENE-WSW. In Box 2, most of the nodal planes show high-angle and low-angle reverse faulting, and some of the high-angle reverse nodal planes show an obliquity associated with a secondary strike-slip motion. Boxes 1 and 2 yield index R' values of 1.75 and 1.85 (Table 1), indicating that both sub-regions are undergoing a transition between pure strike-slip and compressional regimes. Whereas, in the continental interior in Box 2, the inversion shows an index R' of 2.2, suggesting a more dominant compressional regime and less prominent strike-slip regime.

Figure 6: *Results of stress tensors from the inversion of earthquake focal mechanism solution along the western Africa continental margin, offshore and onshore Gulf of Guinea represented by sub-regional boxes (see Fig, 3b).*

Table 1: *Stress parameters associated with the focal mechanism solution of earthquakes in Box 1, Box 2, and Box 3 in Figure 2b. n: number of data used, nt: total data, Pl & Az: plunge & azimuth of principal compressive stress tensors, R': index regime; Reg: Regime, QRfm: Quality rank of focal mechanism.*

4.4 Slip Tendency of Preexisting Fault systems

The application of stress tensors of Box 1 and Box 2 to the fault systems mapped onshore along the coastal margin (i.e., Box 1 sub-region) show that several faults that are more likely to be reactivated if the dominant stress field is that of Box 1 (transpressive with NNE-SSW SHmax; Figs. 7a,c,e,g & 8a,c,e,g). This sub-region covers the Archean rocks of Souanké, the West Congo Belt, and approximately the Inkisi Group. The NNW- and NNE-oriented planes of strike-slip faults showed the highest values of TsN = 80 to 100 %. Also, we note that some of the NNE- and NE-trending normal faults are in a position of reactivation as they show TsN values of >60 %. Here, the WNW- to E-W -oriented faults show the lowest values of TsN, suggesting they could not be reactivated in such stress field. The WNW- to E-W planes are mis-oriented for reactivation as they plot beneath the failure envelope (residual strength envelope) in the Mohr diagram (see blue circles in Figs. 7c, d, g, h & 8c, d, g, h). Overall, the Mohr diagram for the Box 1 regime test indicate that most of the faults are in a position of reactivation.

Whereas, assuming the Box 2 stress field (transpressive with NE-SW SHmax; Figs. 7b, f & 8b, d), very few faults are at failure, suggesting a significantly lower likelihood of reactivation. The possibility of reactivation of the mapped strike-slip faults and normal faults in the Box 2 stress regime is less probable as most of the TsN values are <60 %. Only thrust faults in the West Congo Belt are likely to be reactivated and particularly, the back-thrusts. In Box 2 stress regime, most of thrust faults show TsN values >60%. However, there are a few thrust faults that are in the position of reactivation in the Box 1 stress regime; for example, a major thrust fault system that is associated with the vergence of the orogenic belt (Fig. 8b). Also, in the Box 2 stress regime, the major NE-oriented planes are fault systems that couldn't be reactivated as they plot beneath the failure envelope in the Mohr diagram.

Figure 7: *The application of the stress inversion results for Box 1 (left column) and Box 2 (right column) on Dbk and Dso fault systems and the resulting Slip Tendency values associated with their Mohr-Coulomb stress states. The slip tendency estimate associated with each fault segment is presented as color-coded planes in both the stereoplots and their adjoining Mohr diagrams*.

Figure 8: *The application of the stress inversion results for Box 1 (left column) and Box 2 (right column) on Dwc1 and Dwc2 fault systems and the resulting Slip Tendency values associated with the Mohr-Coulomb stress states. The slip tendency estimate associated with each fault segment is presented as color-coded planes in both the stereoplots and their adjoining Mohr diagrams.*

5 Discussion

5.1 The Stress Regime of Earthquakes along the Western Africa Continental Margin

The regional clustering of earthquakes along and in the vicinity of preexisting tectonic lineaments (Fig. 3a) and the stress tests performed in this study (Figs. 6 - 8) show that earthquakes along the continental margin of western Africa and western Central Africa are likely associated with seismogenic reactivation of preexisting fault systems inherited from past tectonic events. These structures, consist primarily of brittle shear zones developed during the Eburnean orogeny (Proterozoic), Pan-African Orogeny (Proterozoic), and the opening of the Central and South Atlantic (Late Cretaceous). The results of stress inversion and stress tests in this study show that most of the actual fault planes would be NW-SW, NNW-SSE, N-S, NNE to NE-SW and less likely E-W trending strike-slip faults/normal faults or NW-SE and E-W trending thrust-faults in Box 1, Box 2 and Box 3 sub-regions. These faults orientations match most of the described fractures systems in the area and in the literature, particularly for Box 3 (Fig.3). In Box 1 and Box 2 sub-regions, the NW- and E-W -oriented thrust faults probably correspond to the orientation of structures within the West-Congo Belt and thrust sheets of the Oubanguides Belt respectively. Both the strike-slip faults and normal faults deform every unit in the sub-regions from Archean through the Cretaceous units. Also, based on the visited field sites with seismic events, the earthquake epicenters are generally located in the vicinity of the large strike-slip fault systems or normal fault zones. For Box 3, strike-slip faults and normal faults would likely correspond to N-S and NNE-trending strike-slip and thrust fault systems of the Dahomeyide Belt (Affaton et al., 1991; Villeneuve & Cornée, 1994) which were later reactivated either in normal faulting or strike-slip faulting.

The orientations of nodal planes used in stress inversion determination are consistent with the kinematics of some of the strike-slip, normal, and thrust fault systems with high values of slip tendency in Box 1 and Box 2 stress fields applied to these faults systems in the area (Figs. 6, 7, 8). The NNW-SSE and NNE-SSW features would play as dextral strike-slip faults and sinistral strike-slip faults under the stress regime in Box 1. This situation is satisfied in perfectly in Dso fault system of Souanké (Fig.7e) and with some faults in the Inkisi Group (Fig. 7a). For instance, in the coastal margin, the Monatélé earthquake in Cameroon was associated with a NE-SW trending strike-slip sinistral fault (Ngatchou et al., 2018). This clearly supports the kinematics of actual faults plan acting in this coastal margin. From the coastal margin to inland continent, the results show that there is a partition in stress regime within the western central African continental plate. On the coastal margin a strike-slip faulting regime with a minor compressional regime component prevails, while in the inland, the regime is more compressive with a moderate strike-slip faulting component. This explain why NW-SE to NNE-SE strike-slip faults/normal faults show the most tendency to be reactivated in the costal margin areas during the past or present-day. While for the continental interior areas, the most probable reactivated structures are NW-thrust faults/normal faults systems and less likely strike-slip faults. Delvaux et al. (2017) proposed the development of strike-slip deformation of the Inkisi Group during the opening of the south Atlantic and suggested that the event was associated with the last phase of continental break-up with sub-horizontal maximum compressive stress that is oriented N-S. The inferred stress field of the break-up phase is similar to the stress field calculated for the Box 1 stress-field in this study (Fig.6a). This would indicate that the Box 1 stress field was once acting on the cratonic interior sub-regions but is now restricted to the continental margin areas.

Overall, several studies have speculated that preexisting fractures are hosting earthquakes along the continental margins and interior of western Africa but lack details of the ambient stress field and the evidence for coseismic surface fault rupture or presence of active fault scarps (Blundell, 1976; Sykes, 1978; Bouka Biona and Sounga, 2001; Bouka Biona and Sounga, 2001; Ayele, 2002; Amponsah, 2002; Kutu, 2013; Olugboji et al., 2021). Here, with our stress analysis, we provide insight into the control of contemporary stress regimes on the occurrence of intraplate earthquakes in the region.

5.2 The Inherited Weakness of the Preexisting Fault Systems

Our stress analysis shows that the structural geometries of preexisting fault zone fracture surfaces make them favorably oriented for reactivation in the contemporary stress field. However, although fault orientation and their coefficient of friction in the Mohr-Coulomb space may determine whether a preexisting fault can reactivate, they do not determine whether faults would reactivate by stable creep or by seismic rupture. The susceptibility of faults to seismic or stable creep reactivation is determined by the frictional stability of the faulted rocks at the contemporary temperature and pressure conditions at depth in the crust (Blanpied et al., 1998; Dieterich, 1979; Ikari et al., 2011; Marone, 1998). This phenomenon is true for both active plate boundary settings (e.g., Carpenter et al., 2009) and intraplate settings (e.g., Kolawole et al., 2019).

Our field observations of the basement- and sedimentary-hosted fault systems show widespread occurrence of hydrothermal alterations along the fault zones (Fig.5). These hydrothermal alterations include calcite veins, quartz veins, palygorskite gouge fill, a mix of palygorskite and calcite, and iron stains along the fault planes. Also, we note that the fault zones commonly show post-alteration brittle reactivation of the fault zones (e.g., Figs.5b, c, d). The presence of accretion patterns in the calcite realms suggest that there were multiple episodes of hydrothermal incursion into the fault zones. Also, the presence of calcite alterations along fault zones in both the crystalline basement rocks of the West Congo Belt and overlying Inkisi Sandstone units suggest that the large strike-slip fault systems in the sandstone exposures are likely rooted directly into the basement and both structural levels have shared at least one episode of hydrothermal circulation in the past. However, more importantly, the most-common alteration minerals along the fault zones, calcite and palygorskite, are known from laboratory experiments to show frictional instability ($0 > a\text{-}b > -0.013$) at temperature and pressure conditions relevant to a seismogenic depth interval in the upper crust (Kolawole et al., 2019; Sánchez-Roa et al., 2017; Verberne et al., 2015).

Overall, the fault zones investigated in the field are generally dry in present-day. Also, asides from the Cameroon Volcanic Line and the Angolan Bié Dome, hot springs are very rare and there is no large-scale geothermal high-anomaly along the western Africa onshore continental margin areas (Macgregor, 2020; Waring et al., 1965). The occurrence of hot springs in both the Cameroon Volcanic Line and Bié Dome are understandable since both are known zones of localized mantle upwelling (Reusch et al., 2010; Walker et al., 2016). The sparseness of hot springs in the region suggests that seismic reactivation of the intraplate fault zones is not likely driven by crustal circulation of hot fluids. Therefore, considering the widespread occurrence of minerals like calcite, quartz, and palygorskite along the fault zones, we suggest that the seismic stability conditions of the faulted rocks at depth may be contributing to the susceptibility of the onshore fault zones to seismic reactivation.

5.3 Possible Origins of Stress Loading along the Western Africa Continental Margin

Again, aside from the Cameroon Volcanic Line and Bié Dome in Angola, where active mantle processes are driving magmatic activities and associated earthquakes (De Plaen et al., 2014; Tabod et al., 1992; Ubangoh et al., 1997), the origin of stress loading leading to seismogenic rupture of preexisting faults in the onshore areas of the western Africa's continental margin remains controversial and less understood (Olugboji et al., 2021). The proposed mechanisms include the reactivation of local basement fractures by far-field tectonic stresses from mantle processes along the Cameroon volcanic line, post-rift crustal relaxation along the rifted margin, landward continuation of oceanic fracture zones, and induced earthquakes triggered by groundwater extraction (Olugboji et al., 2021).

The zone of earthquake clustering along the Ghanian coastal margin, shown in Fig. 3a, is collocated with NNE-trending Quaternary faults (Akwapim, Lokossa, and Séhoué Faults) which splay northwards from the northeastern tip zone of the Chain Fracture Zone offshore, defining a Reidel horsetail-pattern geometry within the fracture zone (Burke, 1969). However, (Burke, 1969) rightfully noted that there is no evidence of continuity of fault trace further inland from this region. However, just east of the Ghana region, brittle deformation of basement massifs further inland in SW Nigeria show the pervasive presence of satellite-scale ENE-trending fracture systems (Anifowose & Kolawole, 2012) that trend parallel to the near-shore segments of the oceanic fracture zones. Likewise, in this study, onshore large-scale lineament mapping and detailed field mapping of fault systems show the presence of ENE-to-NE-trending fault systems that do not extend directly offshore, but also trend parallel to the near-shore segments of the oceanic fracture zones (Figs. 1, 3a). It was also proposed that channeling of melt along the northeastward extension of the Ascension Fracture Zone across the continent-ocean boundary and further onshore influenced the development of the Cameroon Volcanic Line (Reusch et al., 2010). However, the NE-SW oriented extensional structures would have formed parallel to the shortening axis and approximately to the maximum compressive stress (Woodcock & Schubert, 1994).

In addition to the observation of similar structural trends between oceanic fracture zones and onshore fault and fracture systems, our analysis shows that the stresses acting on the offshore oceanic fracture zones are comparable with the stresses acting along the onshore areas of the continental margin (Figs. 6a-b and 6e); and that the onshore fault systems have a high slip tendency in this contemporary stress field (Figs. 7-8). Given that the oceanic fracture zones are active intraplate faults possibly activated by far-field strain transfer from transform faults along the spreading ridges (Fig. 2a; Meghraoui et al., 2019), we propose that northeastward stress propagation into the near-shore and onshore tip zones of the oceanic fracture zones may be driving stress loading on pre-stressed fault systems onshore, leading to fault reactivation in the onshore areas.

6 Conclusions

In this study, we compute the contemporary stress field along the coastal margin of western Africa and some of the interior cratonic areas, map pre-existing fault systems in basement and sedimentary outcrops along the margin, and access the reactivation potential of the mapped structural planes. Our results show that:

- Intraplate earthquakes along the continental margin of West Africa and western Central Africa cluster along or in the vicinity of preexisting brittle shear zones and thrust faults, suggesting a potential for brittle reactivation of preexisting structures.
- The earthquakes originate under a transpressive stress regime with the maximum principal compressive stress ($\sigma 1$, parallel to SHmax) oriented NNE-SSW.
- In this contemporary stress field, the pre-existing NNE-, NNW-, and N-S -trending strike-slip faults and normal faults show a high slip tendency (60 – 100 %), suggesting a high likelihood to be reactivated. Whereas in the cratonic interior of western Central Africa, the NW- and N-S -trending thrust faults are the most probable structures to be reactivated.
- In both the basement and sedimentary cover rocks, paleo- hydrothermal alterations of the fault zones are common. Although, in present-day, the fault zones are generally dry, the

high likelihood of reactivation (based on our stress tests) and presence of fault rock frictionally unstable materials on fault planes (minerals like palygorskite and calcite) suggest that the faults may be susceptible to frictional instability and earthquake nucleation during their reactivation.

- Our stress analysis show that the regional stresses acting on offshore oceanic fracture zones are compatible with the stresses acting along the onshore areas of the continental margin; and that the onshore pre-existing strike-slip faults, which are parallel to the oceanic fracture zones, have a high slip tendency in this contemporary stress field.
- We propose that northeastward stress propagation into the near-shore and onshore tip zones of the oceanic fracture zones may be driving stress loading on pre-stressed fault systems onshore, leading to fault reactivation in the onshore areas.

Acknowledgments

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This work is part of the PhD thesis of Nkodia Hardy. It is funded by Coopération Belge and ACCORDCAD, under the GEORES4DEV program, for his PhD through the support of the Royal Museum of Central Africa. We thank the reviewers for their great help to improve this manuscript. We also thank Mr. Elvis Kongota and Prof. Valentin Kanda Nkula for their administrative help in Democratic Republic of Congo.

Data Availability Statement

The earthquake data used in this study can be downloaded in the International Seismic Center (ISC), the United States Geological Survey (USGS), the Global Centroid-Moment-Tensor (CMT), and the GFZ GEOFON earthquake catalogs. The focal mechanism data and field measurements that support the analysis in this study are provided in the supplementary documents of the manuscript. The version 5.9.1 of the Win-Tensor free-access software was used to determine stress from focal mechanism and for the assessment of fault slip tendency. The software can be downloaded from http://damiendelvaux.be/Tensor/tensor-index.html (D. Delvaux, 2012).

Credit Author statement

DVMHN: Conceptualization, Methodology, Data Curation, Investigation, Writing-Original; Writing- review & editing; Visualization, Formal analysis, Project administration; **TM**: Conceptualization; Methodology, Investigation; Reviewing; **FK**: Methodology, Writing- review & editing, Visualization, Validation; **FB**: Conceptualization, Investigation, Supervision, Project administration, Funding Acquisition, Reviewing; **APRL**: Investigation; reviewing; **NCBT**: Investigation and reviewing; **DD**: Methodology, Writing- review & editing, Supervision, Investigation; Validation; Resources, Data Curation, Funding Acquisition.

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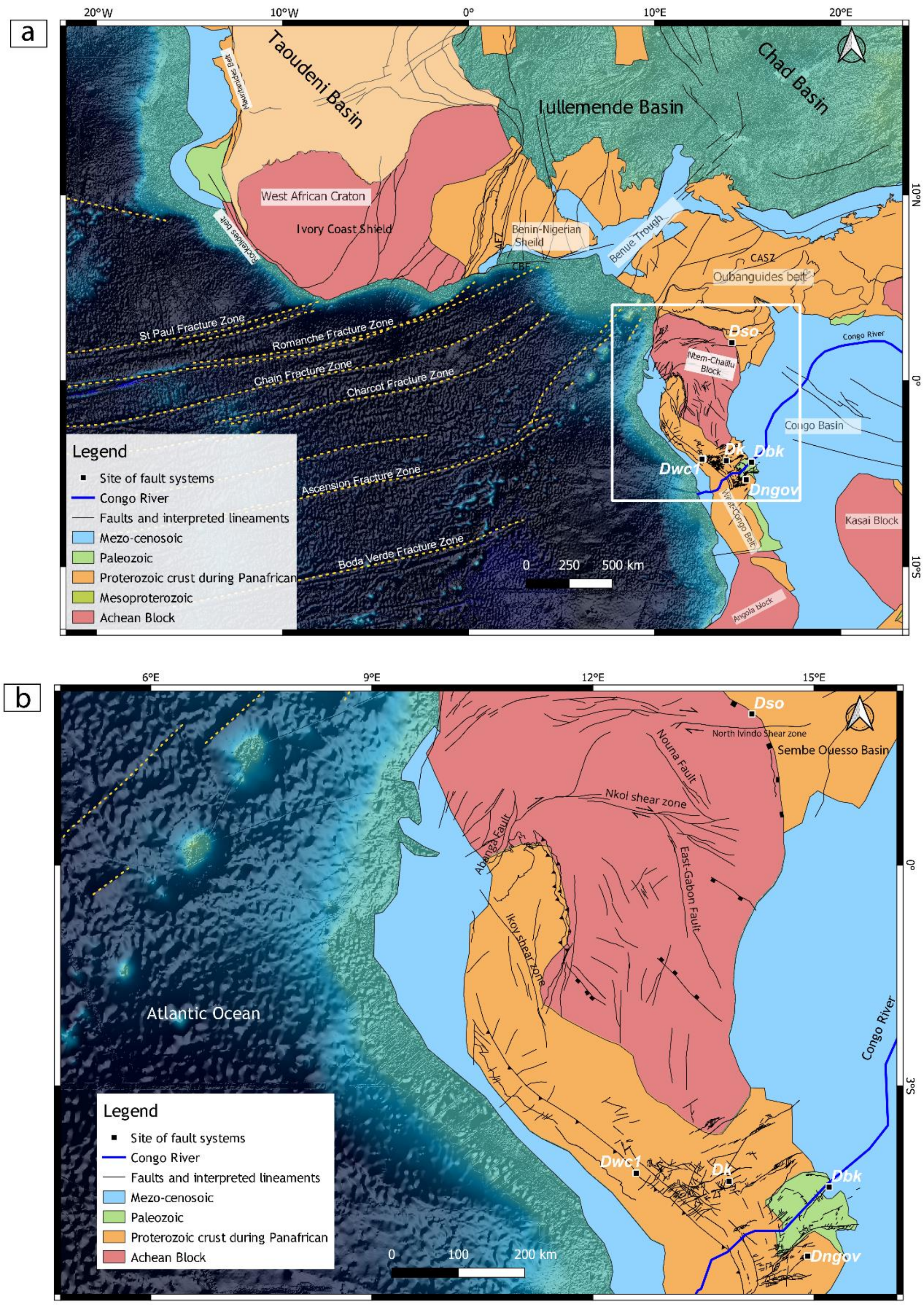

Figure 1: *Map of the bedrock geology of the Nubian Plate showing major litho-tectonic subdivisions of the crust. Dwc1, Dk, Dbk, Dngov, Dso represent field sites where structural measurements of fault systems were collected. Dwc1 represent the study site of a thrust fault system in western Congo. Dwc2 is a combination of strike-slip faults in Dk and Dngov which represent field sites in Kolas Quarry, Republic of Congo, and Ngovo Cave, Democratic Republic of Congo respectively. Dbk represents the field study sites of fault systems in Brazzaville and Kinshasa*

areas. AFZ: Akwapim Fault Zone, BFZ: Bouandary Fault Zone, CASZ: Central African shear zone.

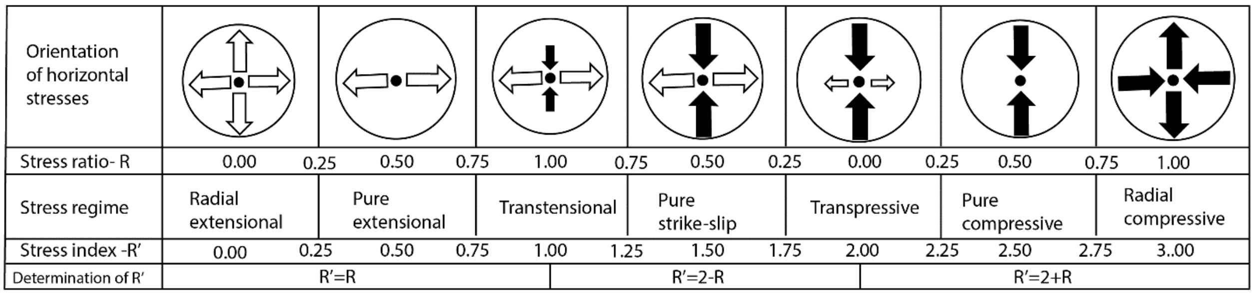

Figure 2: *Standard values of the stress index R' with respect to the various tectonic stress regimes (modified from Delvaux et al., 2017).*

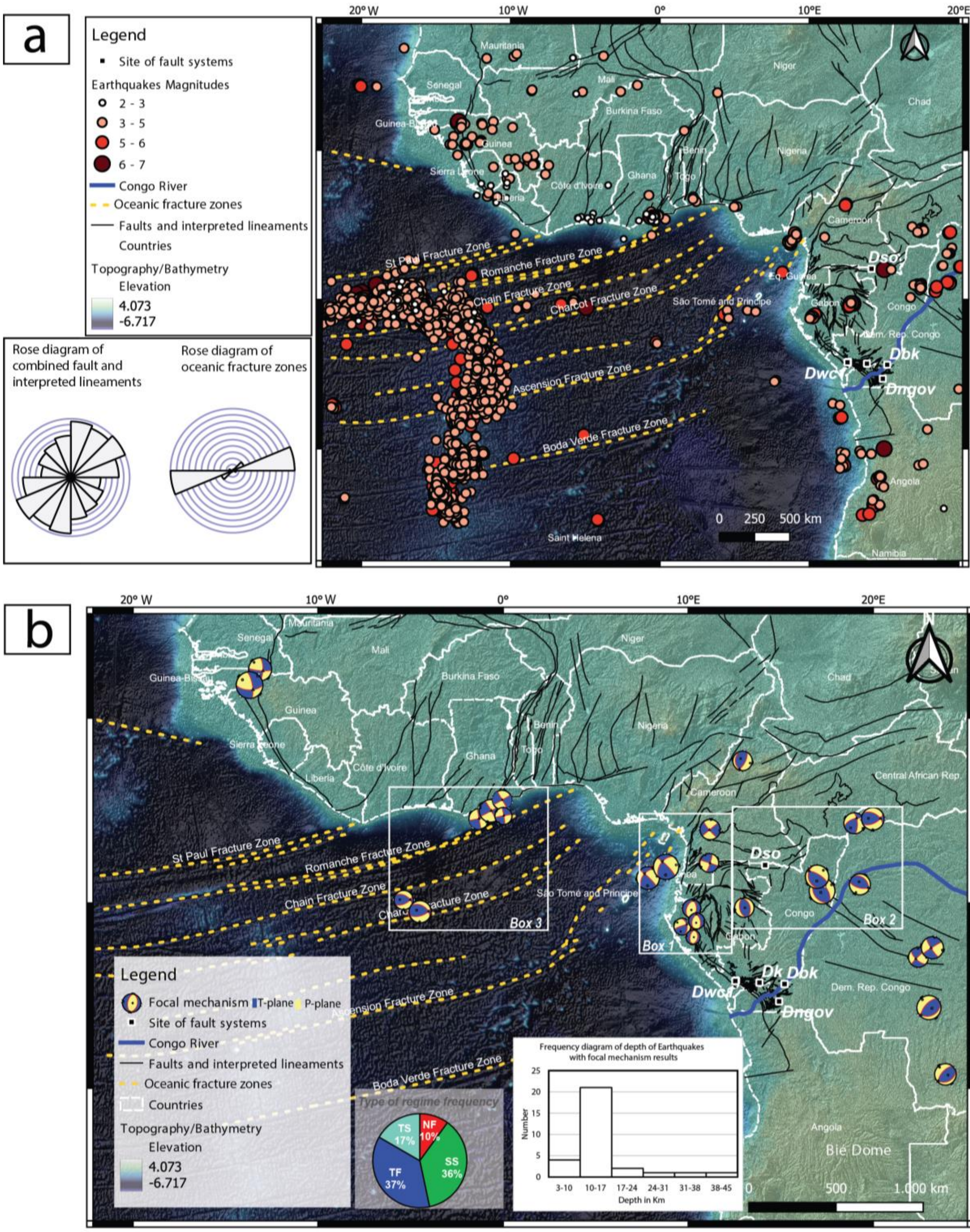

***Figure 3:** (a) Map of the distribution of earthquakes in the Western African passive margin. AFZ, CASZ are the Akwapim Fault zone, the Central Africa shear zone. (b) Focal mechanisms solution for earthquakes in the western part of the Nubia Plate, obtained from several literature review, Global CMT moment tensor, and GFZ GEOFON earthquake catalogs. The boxes show the area where conducted stress inversion on focal mechanism results. The pie-chart show the frequency*

distribution of the different tectonic regime acting on the area. TS: trenstensional regime; NF: normal faulting regime; SS: strike-slip faulting regime; TF: thrust faulting regime.

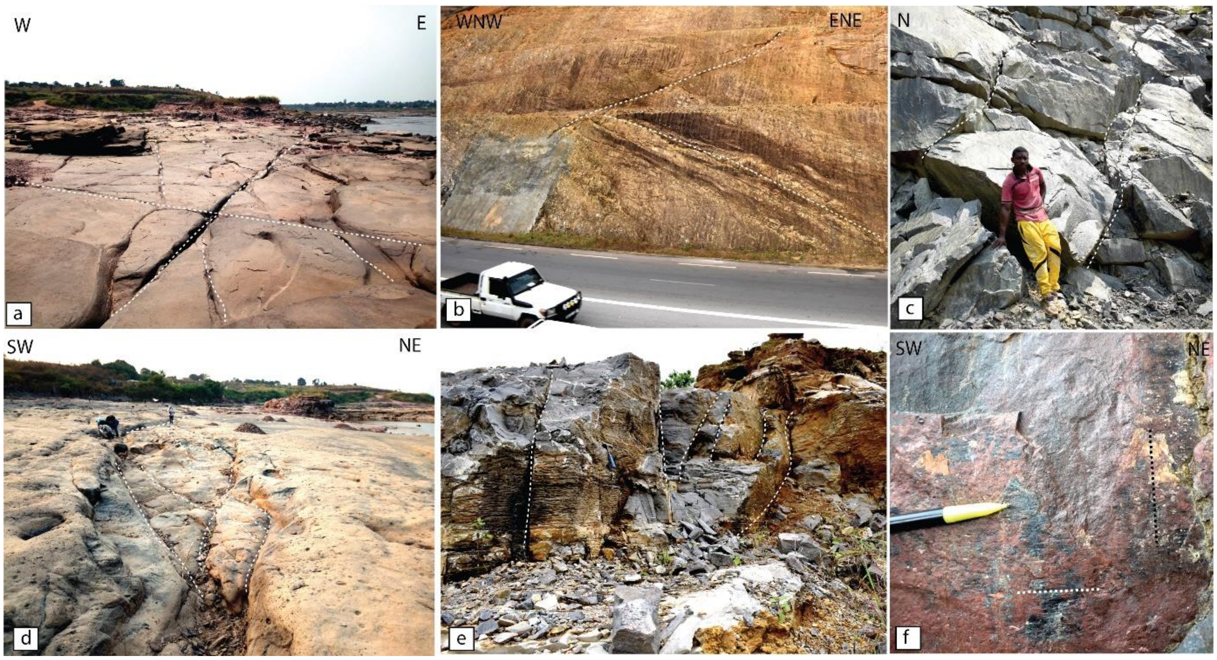

Figure 4: *Field observations of faults systems. (a & d) Fault systems in outcrops of the Inkisi Group (Dbk), showing fracture patterns (highlighted in white dashed line in 3a), and a fault zone showing segmented faults in a duplex zone (in 3d), at the Kombé quarry, located near the Congo River, Brazzaville. (b & e) Faults systems (Dwc1 & Dk) in the West-Congo Belt showing successively thrust and back-thrust affecting schists and quarzites, in Dolisie along the RN1 primary road, and strike-slip fault planes in Kolas quarry near Loutété region. (c & f) Faults systems (Dso) in Souanké showing high-angle planes of strike-slip faults in the area (in 3c) and, a NE-trending plane that shows horizontal striae that is over-printed by vertical striae associated with calcite fibers, indicating a later normal faulting reactivation of the strike-slip faults. The dashed lines in Fig. 3f represent the directions of striae.*

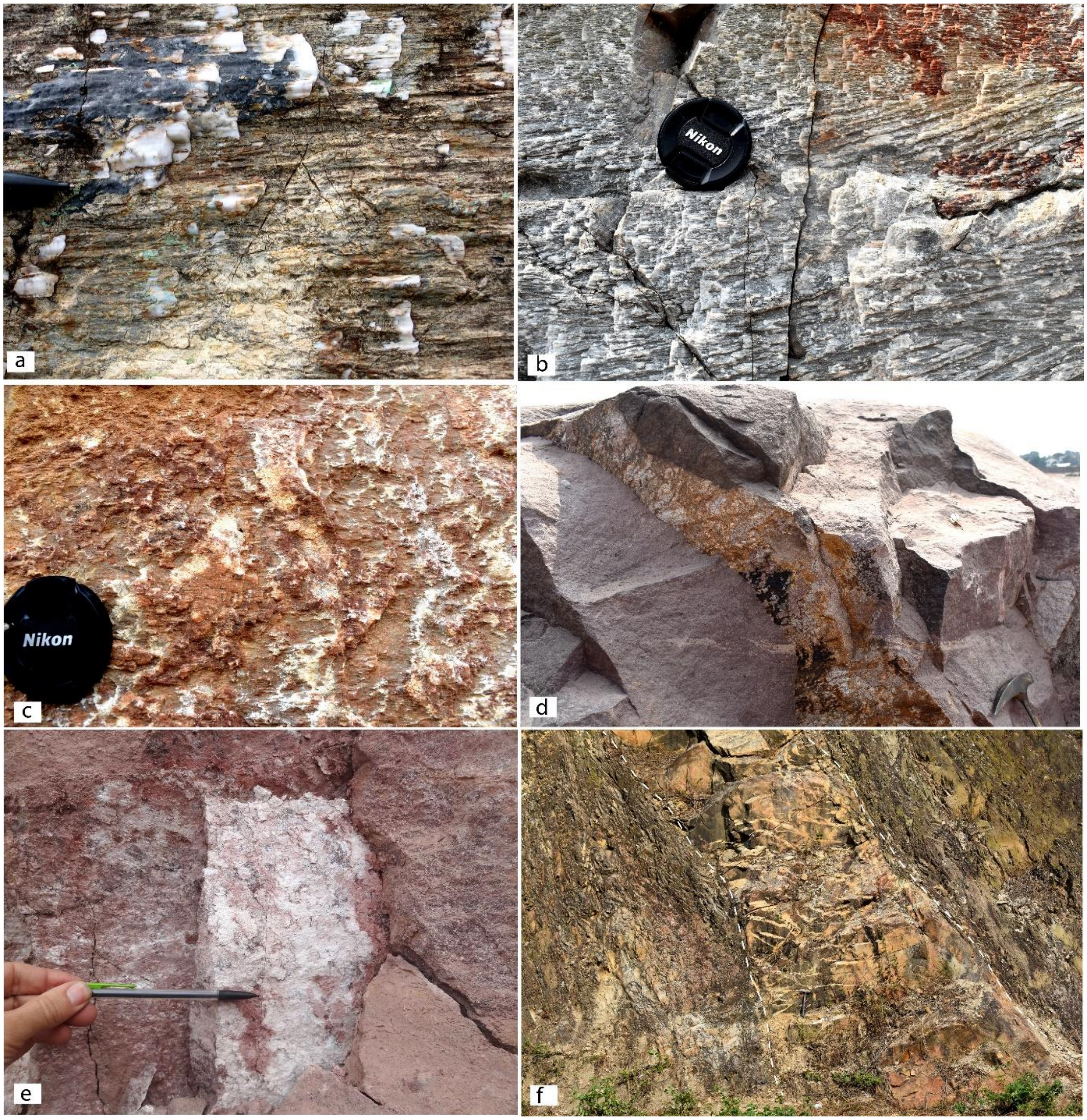

Figure 5: *Geochemical alterations along mineralized fault surfaces. (a) Accretion calcite steps along NW-SE strike-slip faults in carbonates rocks of the West Congo Belt, DRC. (b - c) Carbonate-hosted fault surfaces covered by accretion calcite steps and iron staining. Note that the carbonate rock in Figure 5b has penetrative cross-bedding structures that should not be confused with slickenlines. (d) Fault surface in Inkisi sandstones associated with iron alteration realm. (e) Slickensided palygorskite along a fault in Dbk fault system. (f) Deformed doleritic intrusion along a high-angle thrust-fault (230/40) injected with quartz veins in the Dwc1 fault system.*

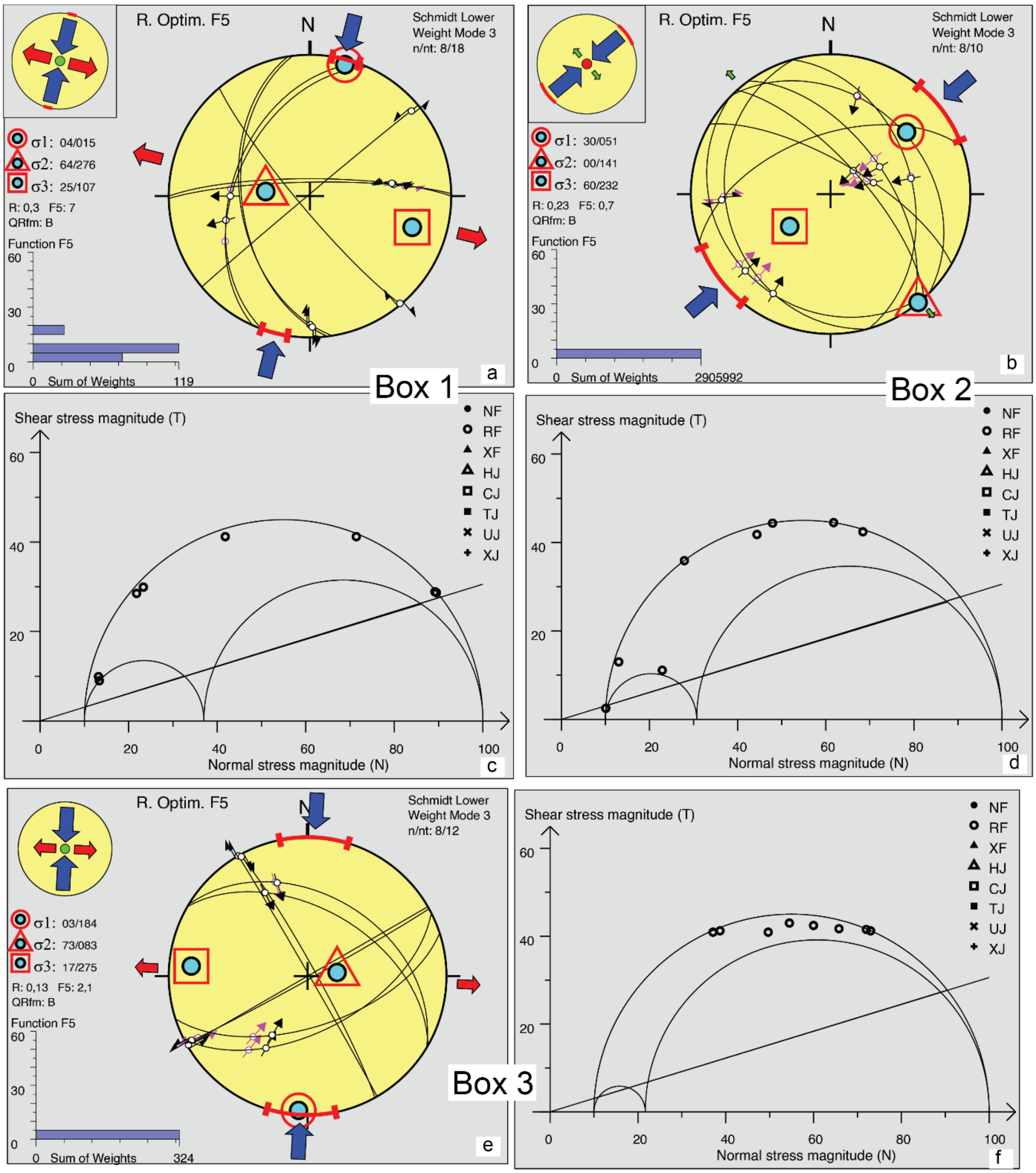

Figure 6: *Results of stress tensors from the inversion of earthquake focal mechanism solution along the western Africa continental margin, offshore and onshore Gulf of Guinea represented by sub-regional boxes (see Fig, 3b).*

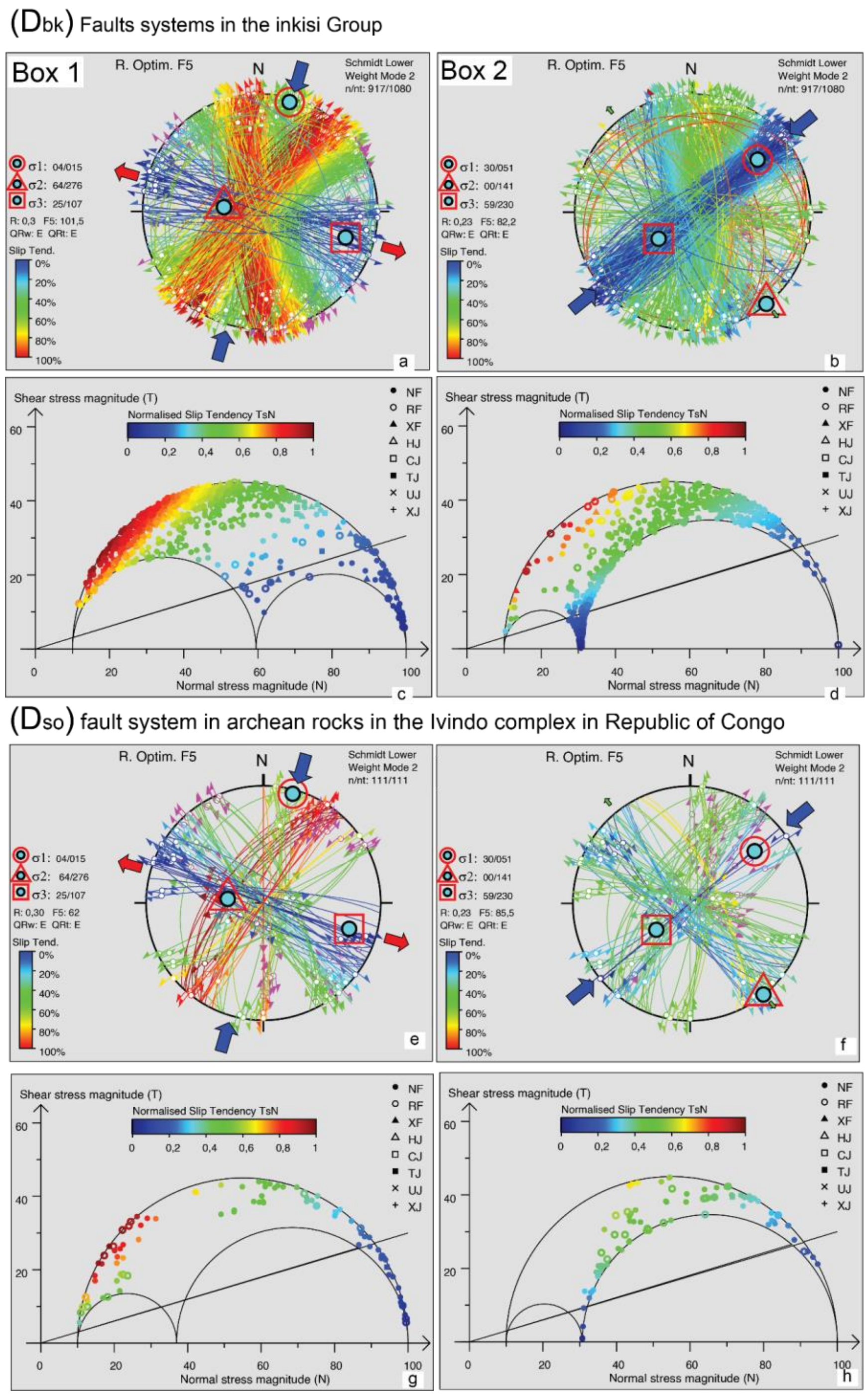

Figure 7: *The application of the stress inversion results for Box 1 (left column) and Box 2 (right column) on Dbk and Dso fault systems and the resulting Slip Tendency values associated with their Mohr-Coulomb stress states. The slip tendency estimate associated with each fault segment is presented as color-coded planes in both the stereoplots and their adjoining Mohr diagrams.*

Table 1: *Stress parameters associated with the focal mechanism solution of earthquakes in Box 1, Box 2, and Box 3 in Figure 2b. n: number of data used, nt: total data, Pl & Az: plunge & azimuth of principal compressive stress tensors, R': index regime; Reg: Regime, QRfm: Quality rank of focal mechanism.*

Stress parameters	*n*	*nt*	*σ1*		*σ2*		*σ3*		*Reg*	*QRfm*	*R'*		*Shmax*	*Shmin*
			Pl	*Az*	*Pl*	*Az*	*Pl*	*Az*			*Value*	*meaning*		
Box 1- West Central	8	18	4	15	64	276	25	107	SS	B	1.75	Transpressive	14	102
Box 2- Continental interior	8	10	30	51	0	141	60	232	TF	B	2.2	Transpressive	49	40
Box 3- Western Coastal Margin	8	12	3	184	73	83	17	275	SS	B	1.87	Transpressive	3	93