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Plates Amalgamation and Plate Destruction, the Western Gondwana History

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1. Introduction

Reconstruction of the western Gondwana tectonic setting is a highly challenging topic. Orogenic belts are generally outlined by mountain ranges or the so commonly called "mobile zones" in old shields. They define linear belts following the suture of two plates amalgamated during collision and whose boundaries are usually clearly identifiable. Most often, the original geotectonic settings of the mobile zone are also clearly outlined by sedimentary, magmatic, metamorphic, structural and isotopic zonings that render the reconstructions of the belt relatively easy. Contrastingly, the Pan-African/Brasiliano tectonic setting in western Gondwana corresponds to a broad area that shows no specific orientation and, except at the eastern border of the West African Craton (WAC), plate boundaries, belt polarity and zoning are intensely obliterated by the branching geometry of the regional strain, the intense and widespread deformation, migmatization and granitization, particularly at its extensions towards the northwestern Cameroon and eastern Sahara (Fig.1). These particular features render geotectonic interpretations of the Pan-African mobile zone extremely complex. Thus, the tectonics of western Gondwana appears as a controversial topic and a matter of contention, both in old and recent studies (e.g. Paulsen et al., 2007; Tucker et al., 2007; Goscombe & Gray, 2008; Vaughan & Pankhurst, 2008; Casquet et al., 2008). Indeed, despite the existence of good petrologic and isotopic data and a relatively clear definition of the regional geochrono-stratigraphy in the Pan-African domain of Cameroon and northwestern regions, the lack of detailed structural studies has generated controversial tectonic models. This intermediate domain between the West African Craton (WAC), the São Francisco- Congo Craton (SFCC) and the enigmatic east Saharan craton is currently interpreted either as a Dahomeyan-related basin and range province including meridian directed troughs (Affaton et al., 1991; Castaing et al., 1994), a Neoproterozoic branching belt including numerous micro-plates (Trompette, 1994 and references therein; Toteu et al., 2004; Penaye et al., 2006), or a tectonic indent resulting from the collision between the eastern Sahara rigid prong (ESB) and the northern active margin of the SFCC differentiated into a basin and range province overriding a subduction zone (Ngako et al., 2008). We present in this chapter the more recent model completed with further insights on the Post Pan-African evolution of the belt and inferences to further developments of the western Gondwana.

This study involves modern structural analysis and concepts (phase chronology, strain analysis, deformation and kinematics), petrology (metamorphic parageneses and phase equilibrium, relation with deformation, geothermobarometry), geochemistry (major and trace elements) and geochronology. Data from regional literature including geophysical data are also abundantly used for synthesis and re-interpretation. The most important achievements include:

1. A new tectonic model for the Pan-African/Brasiliano belts; this model includes many original aspects and developments with regards to the collisional setting, tectonics, metamorphic and magmatic processes. In particular, a three-plate model is proposed, and the role of the asthenosphere on crustal melting and reactivation during collision is emphasized.

2. Evidence of a tectonic indent in the central Nigeria-Cameroon domain, inferred from the regional strain field; indentation in central-west Africa strongly suggests that the East Saharan Block (ESB) evolved originally as a rigid prong prior to crustal melting, batholiths emplacement and subsequent dismantling of the prong during the late Pan-African evolution.

3. Clear distinction between Pan-African and Post Pan-African tectonic and magmatic processes which raises the question on the relevance of integrating Phanerozoic lithospheric structures inferred from geophysical data (gravity, seismic tomography, etc.) in the interpretation and reconstruction of the Pan-African tectonic evolution.

Future research would be focused on the Central Cameroon Shear Zone (CCSZ) kinematics and the characterization of vestiges of the dismantled SFCC/ESB cratons and hypothetic pre-tectonic boundaries.

2. Plates amalgamation in western Gondwana

2.1 Orogenic setting and major plate boundaries
2.1.1 The Sao-Francisco-Congo Craton (SFCC) northern boundary

Recent petrologic and isotopic data enable define three Pan-African main geotectonic units at the northern border of the SFCC: the Poli Group (northern Cameroon), the Adamawa domain (central Cameroon) and the Yaoundé Group (southern Cameroon). They likely represent an original basin and range province (Fig.1 & Fig.2).

The Poli Group represents an early Neoproterozoic back-arc basin formed between 830 and 665 Ma (Toteu, 1990; Penaye et al., 2006; Toteu et al., 2006), that includes: detrital and volcaniclastic deposits, metavolcanics (tholeitic basalts and calc-alkaline rhyolites), and pre-, syn- to late-tectonic calk-alkaline intrusions (diorites, granodiorites and granites). These intrusions, emplaced between 660 and 580 Ma (Toteu et al., 2001) form a NNE-SSW corridor referred to as the West Cameroon Domain or WCD (Fig. 2; Toteu et al., 2004; Penaye et al., 2006). They show a north to south potassium increase from LKT to shoshonites that suggests the existence of a southward dipping suture zone to the North (Njonfang et al., 2006). The Massenya-Ounianga (MO) heavy gravity line in Chad (mean values bracketed between 10 and 30 mGal; Poudjom Djomani et al., 1995) likely materializes obducted fragments of an oceanic floor onto the opposite cryptic margin, as suggested by its superimposition upon thick effective elastic thickness curves (Poudjom Djomani et al., 1995; Fig. 2). The concave geometry of these curves to the North suggests a northward extension of a hypothetic paleo-plate in eastern Sahara, represented by inferred cratonic areas located there (Küster & Liegeois, 2001; Fig.1 & Fig.2).
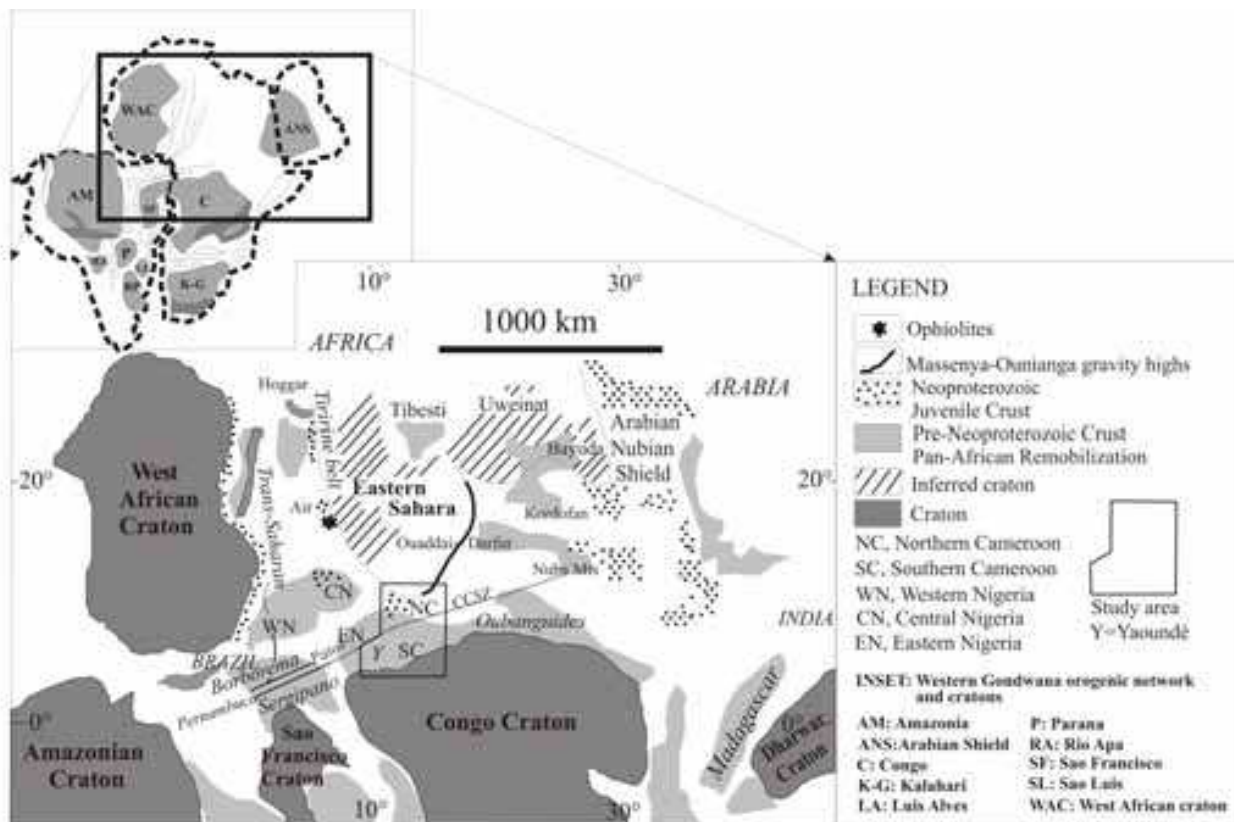
Fig. 1. Sketchy tectonic map of western Gondwana and main geotectonic units (redrawn from Küster & Liegeois, 2001)

The Adamawa domain includes huge Pan-African batholiths and large scale Paleoproterozoic remnants that were emplaced and metamorphosed during the Pan-African tectonic evolution. They represent the basement of the Poli and Yaoundé Groups and likely correspond to the northern and reactivated extension of the Eburnean Nyong series (north-western corner of the Congo craton) within the mobile zone (Fig.2).

The Yaoundé Group represents a syntectonic basin which deposition age is younger than 625 Ma (U-Pb dating of detrital zircons, Toteu et al., 2006). It includes meta-sediments (shales, greywackes, minor quartzites, dolomites and evaporites) and pre- to syn-tectonic alkaline to transitional intrusions represented by pyroxenites, pyroxene-amphibole and pyroxene-plagioclase rocks (Nzenti, 1998); scarce outcrops of serpentinized ultramafic rocks associated with gabbros, diorites and mafic dykes are also found (Seme Mouangue, 1998; Nkoumbou et al., 2006). All these rocks were metamorphosed in the HP-HT granulite facies at ca 620 Ma (U-Pb zircon age by Penaye et al., 1993) prior to exhumation and thrusting over the Congo craton.

2.1.2 The West African Craton (WAC) eastern boundary

The eastern border of the WAC (Fig.1) contains several Archaean to Proterozoic inliers, strongly affected by the Pan-African orogeny. For example, the Tuareg Shield, comprising the Hoggar domains, includes Archaean terranes possibly amalgamated during the Eburnean Orogeny and intruded by 640-580 Ma Pan-African granites. Collision of this Shield with the west African Craton is recorded in the strongly deformed Pharusian Belt which includes ophiolites and arc-related volcanic rocks (Begg et al., 2009 and references
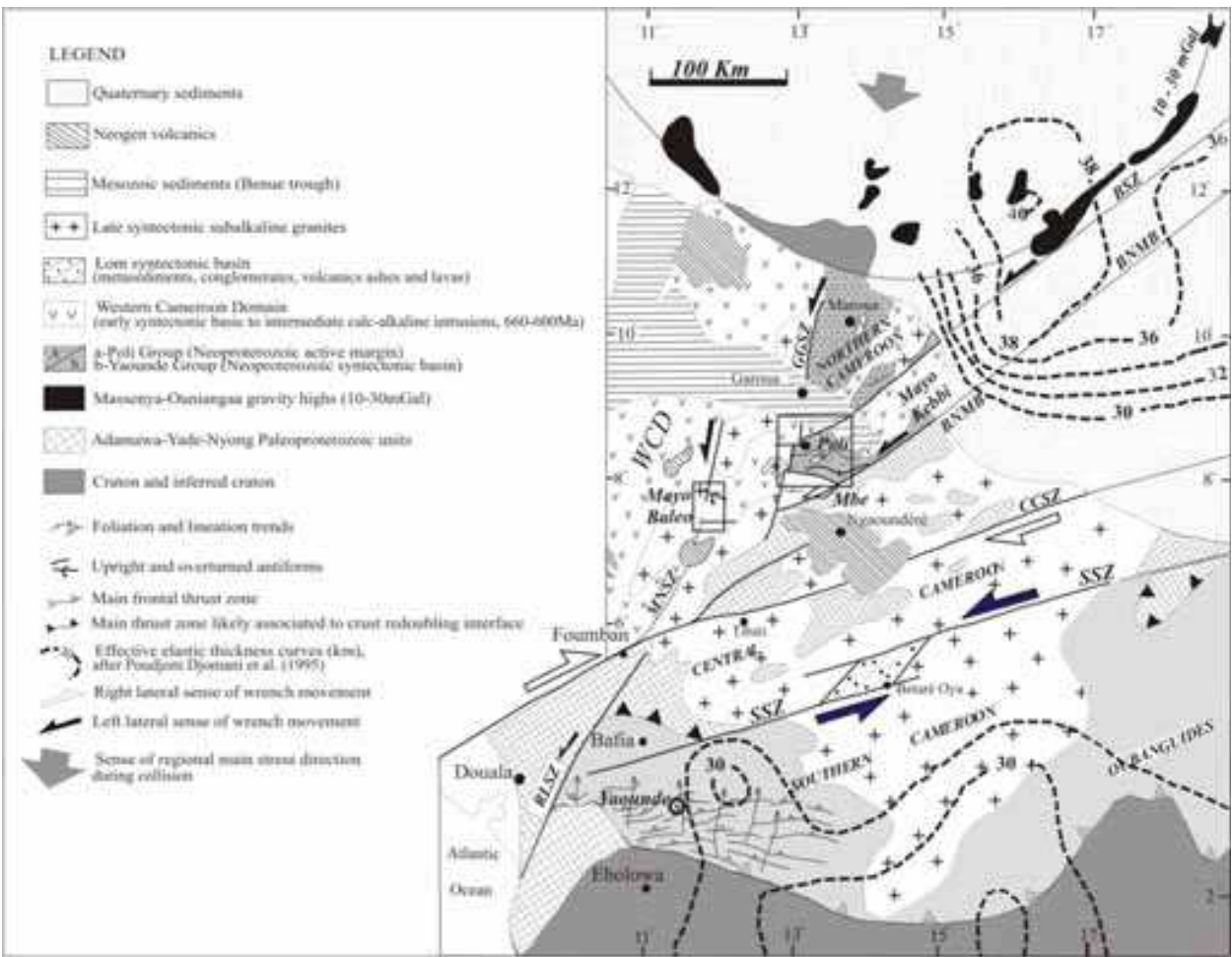
Fig. 2. Structural map of the Cameroon domain (see location in Fig.1)

therein). The WAC boundary is then outlined by a NS-directed linear suture zone revealed by the presence of a high gravity line and the occurrence of ultramafic rocks (ophiolites) straddling parallel to the craton edge in association with ultra-HP metamorphic rocks (eclogites); these features characterize an inter-plates boundary. They mark the transition between the intracratonic Gourma trough and Volta platform deposits and their metamorphic equivalents within internal zones of the Pan-African Trans-Saharan belt.

2.1.3 The Eastern Sahara Block boundary

Except in the Tibesti Archean area (Abdelsalam et al., 2002), the Eastern Sahara Block (ESB, Fig.1) mostly exhibits Pan-African imprints (metamorphism and intrusive) in contrast with the WAC and the SFCC cratons. However, the presence of a stable continental block in eastern Sahara prior to Pan-African events is inferred from the relative position of the Pan-African active margins and back-arc associated volcanics and intrusive rocks in Poli and Central Nigeria (Ferré et al., 2002), the occurrence of an ophiolite complex in SE Air at the southern extension of the Tirririne belt, and the evidence of thick effective elastic thickness characterizing high strength and old tectonothermal ages of the lithospheres across the Massenya-Ounianga high gravity line (Poudjom Djomani et al., 1995). These features suggest the presence of a nearby inter-plates boundary between the Cameroon-Nigeria-Hoggar polycyclic domain and the eastern Sahara (Fig.1 & Fig.2).

2.2 Collision and post-collision evolution

Three main tectonic events related to Pan-African collision and post-collision evolution have been identified in Cameroon: i) crustal thickening; ii) left lateral wrench movements; and iii) right lateral wrench movement, successively.

2.2.1 Crustal thickening (ca 630-620Ma)

a) Fn (F1) isoclinal fold associated to an earlier flat-lying foliation So/Sn refolded by gentle upright folds Fn+1 (F2) in metabasalts. F1/F2 coaxial axes are horizontal at N110. Vertical plane view (Houle, Poli Group)

b) Fn (F1) sheath-like folds in banded amphibolites overprinted by Fn+2 (F3) mini-folds. F1 axial traces are subvertical at N110. Horizontal plane view (South Mango, Poli Group)

c) Fn+1 (F2) recline folds verging to the south in banded metarhyolites. F2 axes at N95-20E. Vertical plane view (Damboulko, Poli Group)

d) Upright Fn+1 (F2) tight folds showing intensely stretched and laminated limbs in banded metabasalts. F2 axes at N100-30W. Horizontal plane view (Damboulko, Poli Group)
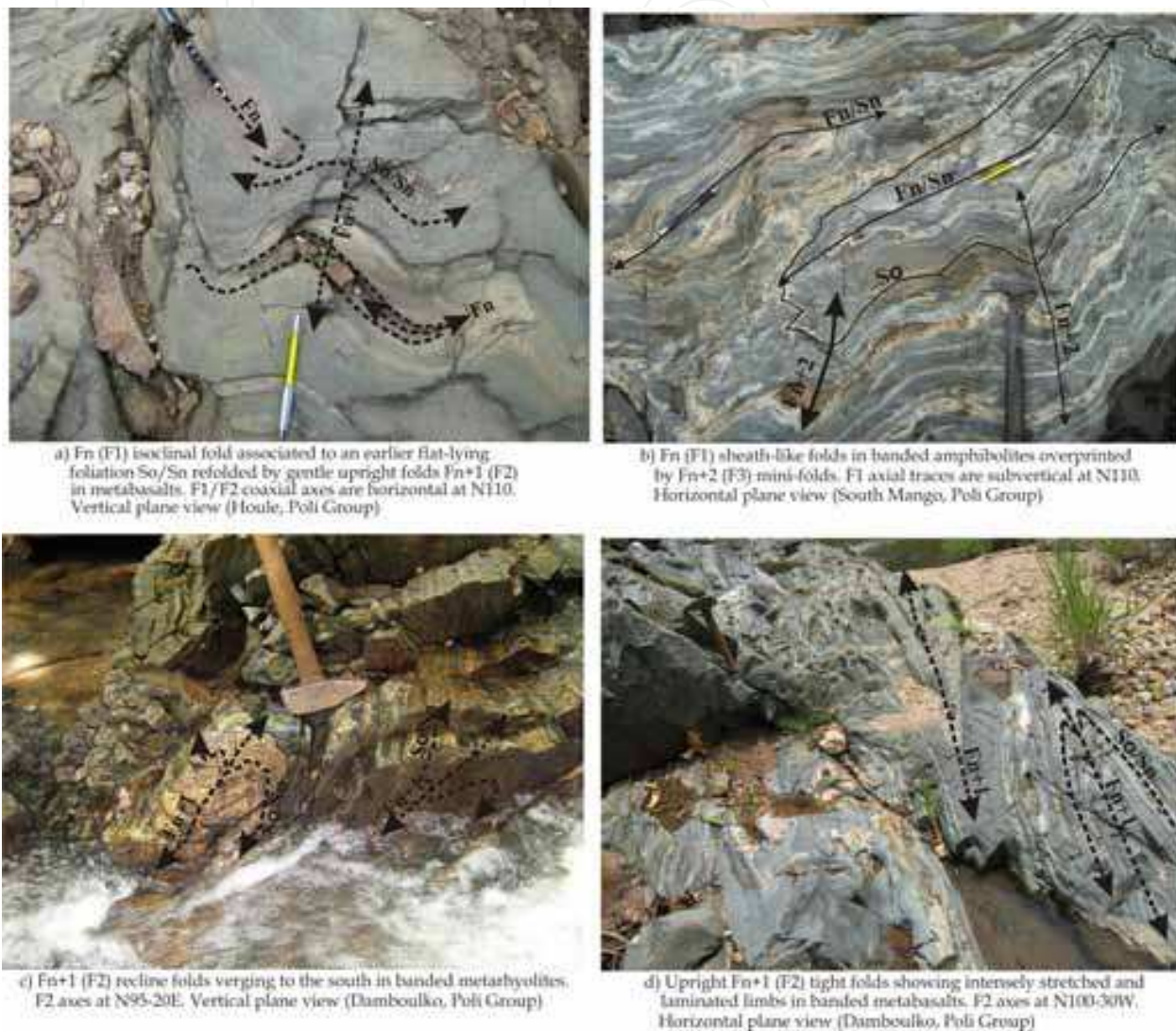
Fig. 3. Fold generations and geometry in Northern Cameroon (Poli Group)

The early Pan-African tectonic evolution includes thrusting and shortening that resulted in crustal thickening. In the Poli region, E-W antiform and synform characterize gentle folding of a regional flat-lying foliation and lineation probably formed during an early thrust evolution (Fig. 3a, c and d). Sheath-like folds coeval with the early foliation materialize intense shear deformation during thrusting (Fig. 3b). The restoration of the folded mineral lineation in primary horizontal position using cyclographic methods enable approximate the kinematic direction to NS during the thrust evolution (Ngako et al., 2008). The HP-HT metamorphic parageneses formed in metapelites, metagranodiorites and basic granulites during thrusting were further retrograded in the amphibolite facies and metamorphic

evolution terminated with synkinematic growth of garnet porphyroblasts in the greenschist facies (Ngako et al., 2008; Bouyo et al., 2009).

At the regional scale, subsequent folding of the nappe resulted in the forming of upright to recline folds. In the Poli region, their geometry varies eastwards, from open to tight profiles, correlatively with a progressive change of the axial plane cleavage from crenulation to mylonitic at the contact zone with the Buffle Noir–Mayo Baléo Shear Zone (BNMB). Further to the South, in the Mayo Baléo region, these folds are overturned westwards, indicating large scale thrust movements coeval with E-W stretching lineations (Ngako et al., 2008). Pb-Pb evaporation ages of ca 600±27 Ma on monozircons from syn-thrust intrusions in Mayo Baléo give an age approximation, though imprecise, of this second folding phase (Ngako, 1999).

a) view of the general flat-lying foliation Sn+1 (S1//S2) of the Yaounde nappe (Olembe quarry)

b) Fn+1 (F2) sheath-like fold with nose facing to the South (second phase nappe, Olembe quarry)

c) Foliation boudinage of S1//S2 flat-lying foliation involving conjugate shear zones dipping to the north and to the south, respectively (Olembe quarry, Yaounde nappe)

d) Interpretation of conjugate shear zones as intra-nappe coaxial markers associated to the southward translation of the second phase nappe (=transpression regime, Olembe quarry)
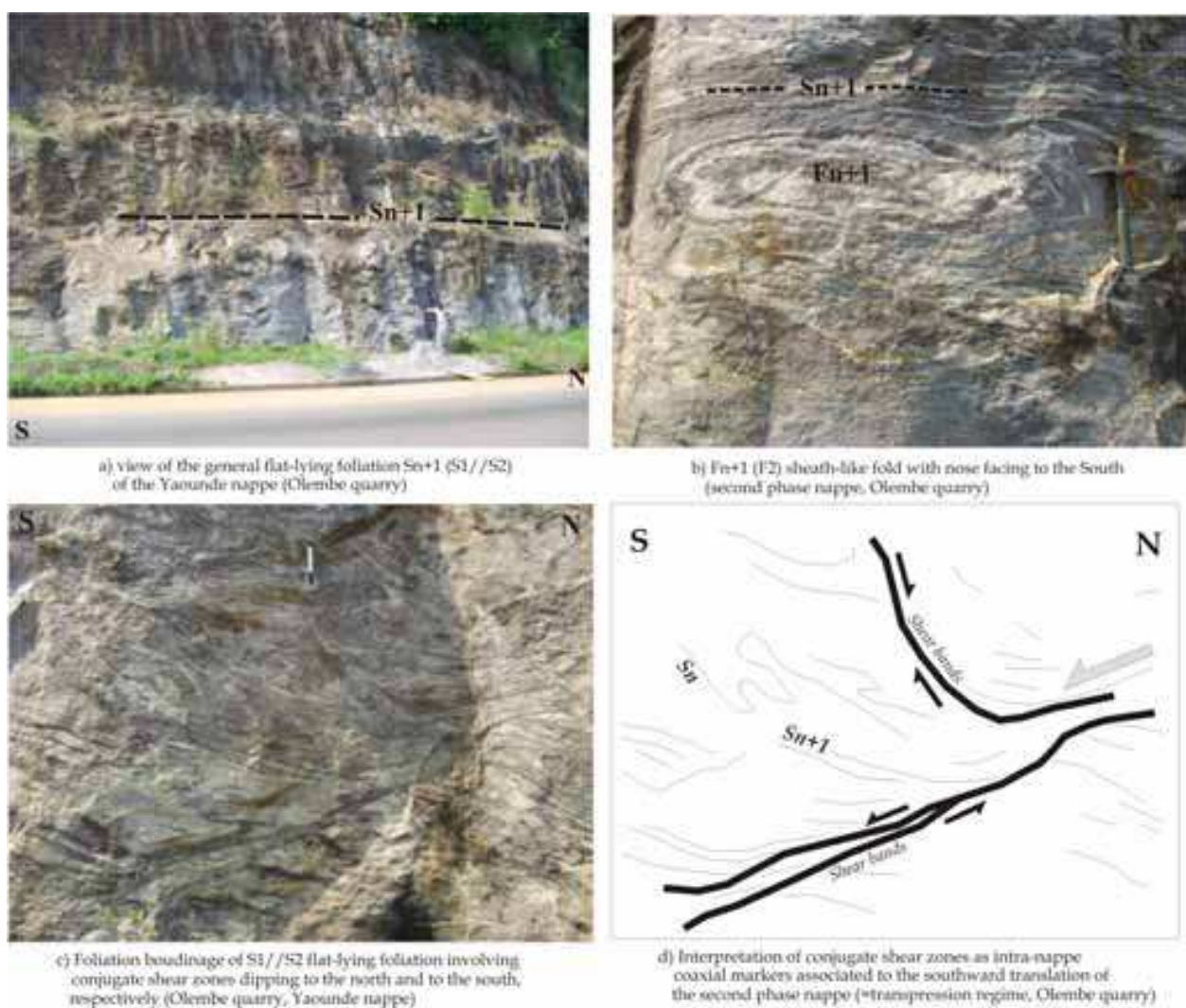
Fig. 4. Internal structure of the Yaoundé nappe and inferred kinematics (Olembe quarry)

Further to the South in the Yaoundé Group, the second phase recline folding includes sheath-like folds associated to horizontal stretching lineation at N20 coeval with foliation boudinage and conjugate shear zones (Fig. 4). These structures suggest interaction between pure and simple shear deformations compatible with late transpressional evolution of the Yaoundé granulites. Metamorphic conditions during the granulite evolution culminate at

10-12 kbar/800°-850°C (Barbey et al., 1990) which are the P-T conditions prevailing at the base of the crust. Thus, the early nappe stacking in the Cameroon domain in whole is compatible with crust redoubling and burial of the Yaoundé Group. Concordant ages of ca 630 ± 5 Ma (Toteu et al., 1990) and ca 620±10 Ma (Penaye et al., 1993) on syn-metamorphic zircons in the Poli micaschists and in the Yaoundé granulites give a good age approximation of this early thrust event, suggesting a north to south successive stacking at regional level.

Reversely, the gradual P-T decrease recorded during the second phase folding (Barbey et al., 1990; Mvondo et al., 2003), suggests that the Yaoundé HP-HT granulites were uplifted (exhumation) during regional shortening. Prominent features during this evolution include: (i) a reverse metamorphic gradient marked by northwards increase of metamorphic intensity from the Mbalmayo schist situated at the sole of the nappe, near to the contact zone with the craton towards the Yaoundé migmatites and gneisses; and, (ii) a southwards increase of the deformation intensity, marked by the progressive decrease of the intersection angles between early foliation and thrust plane from the Yaoundé migmatites to the Mbalmayo schists. This angle varies from nearly 45° (partial rotation of foliation into parallelism to thrust plane in the Yaoundé gneisses), to 0° (foliation//thrust plane) in the Mbalmayo schists where C'-type shear zones of Berthé et al. (1979) are widespread. P-T conditions range from 4-9 kbar/675-575°C in the Mbalmayo schists to 7-12 kbar/ 800°-550°C in the Yaoundé migmatites (Mvondo et al., 2003). An alternative interpretation of the exhumation of HP-HT granulites in the Yaoundé Group suggests it is linked with late Pan-African extensional evolution (Mvondo et al. 2003, 2007); this interpretation is neither compatible with the important crust thickness (38-42 km) in the Yaoundé region (Poudjoum Djomani et al., 1995), nor with the Adamawa Tertiary uplift situated far to the north as suggested by the authors.

The Rocher du Loup shear zone (RLSZ, Fig. 2) represents a lateral ramp accommodating late horizontal displacements parallel to the Nyong rigid promontory during thrust movements onto the Congo craton (Jégouzo, 1984). This promontory would have obliterated the reverse limb of associated large scale recline fold and correlative metamorphic isograds as suggested by a recent study of the Boumyebel talcshist (Yonta-Ngoune et al., 2010). U-Pb ages of a syn-shear syenite yield ca 590 Ma (Toteu et al., 1994), that approximately date the wrench and thrust evolution in southern Cameroon.

2.2.2 Wrench evolution
Early Pan-African folds and nappes in Cameroon are cross-cut by a complex shear zone network with complex kinematics.

2.2.2.1 Left lateral wrench movements (613- 585 Ma)

2.2.2.1.1 The northern and central Cameroon shear zones

These shear zones form two main sets represented by major and synthetic shear zones directed N50°E and N-S, respectively (Fig. 2). Major shear zones include the Balché (BSZ) and the Buffle Noir-Mayo Baléo Shear Zones (BNMB), whereas synthetic shear zones are represented by the Godé-Gormaya (GGSZ) and the Mayo Nolti Shear Zones (MNSZ). The Sanaga fault in central Cameroon is a N70-directed SZ marking a major structural boundary between the northern Cameroon characterized by intense shear deformation, and the southern Cameroon where equivalent regional structures are quite absent. An exhaustive study of these shear zones is provided in Ngako et al. (2008), and only the most illustrative per set is presented in this section.

2.2.2.1.1.1 The Buffle Noir – Mayo Baléo (BNMB) Shear Zone

The BNMB Shear Zone is the most representative major sinistral shear zone. This shear zone (Fig. 2) marks the south-eastern contact between the Poli Group and the gneiss units. It cross-cuts the gneisses in the Mbé area where a three-dimension exposure may be observed; the Mbé quarry (Fig. 5) displays alternating metric bands of coeval steep dipping mylonites and upright folds (Fig. 5a). In the YZ plane, various fold profiles (open, tight, sheath-like, crenulated, dissymmetric and sigmoid) can also be observed (Fig. 5 b and c). The fold axes are parallel to mineral stretching lineation and plunge between 20-35° to SW. Most kinematic markers associated with the mylonite bands are foliation sigmoid shapes, σ-type

a) Internal morphology of the N50-directed BNMB shear zone. Note the sharp tectonic contact between the SZ marked by vertical mylonites C/Sn+1/S2 (left) and the refolded Sn (S1) gneiss foliation (right); Fn+1 (F2) plunge 20-30SW. Mbe quarry (southeastern contact of the Poli Group)

b) Complex association of Fn+1 (F2) sheath-like folds in the BNMB shear zone. Mbe quarry

c) Vertical mylonites exhibiting tight Fn+1 (F2) folds or isolated hinges; also note opened section of a sheath-like fold to the right. Mbe quarry
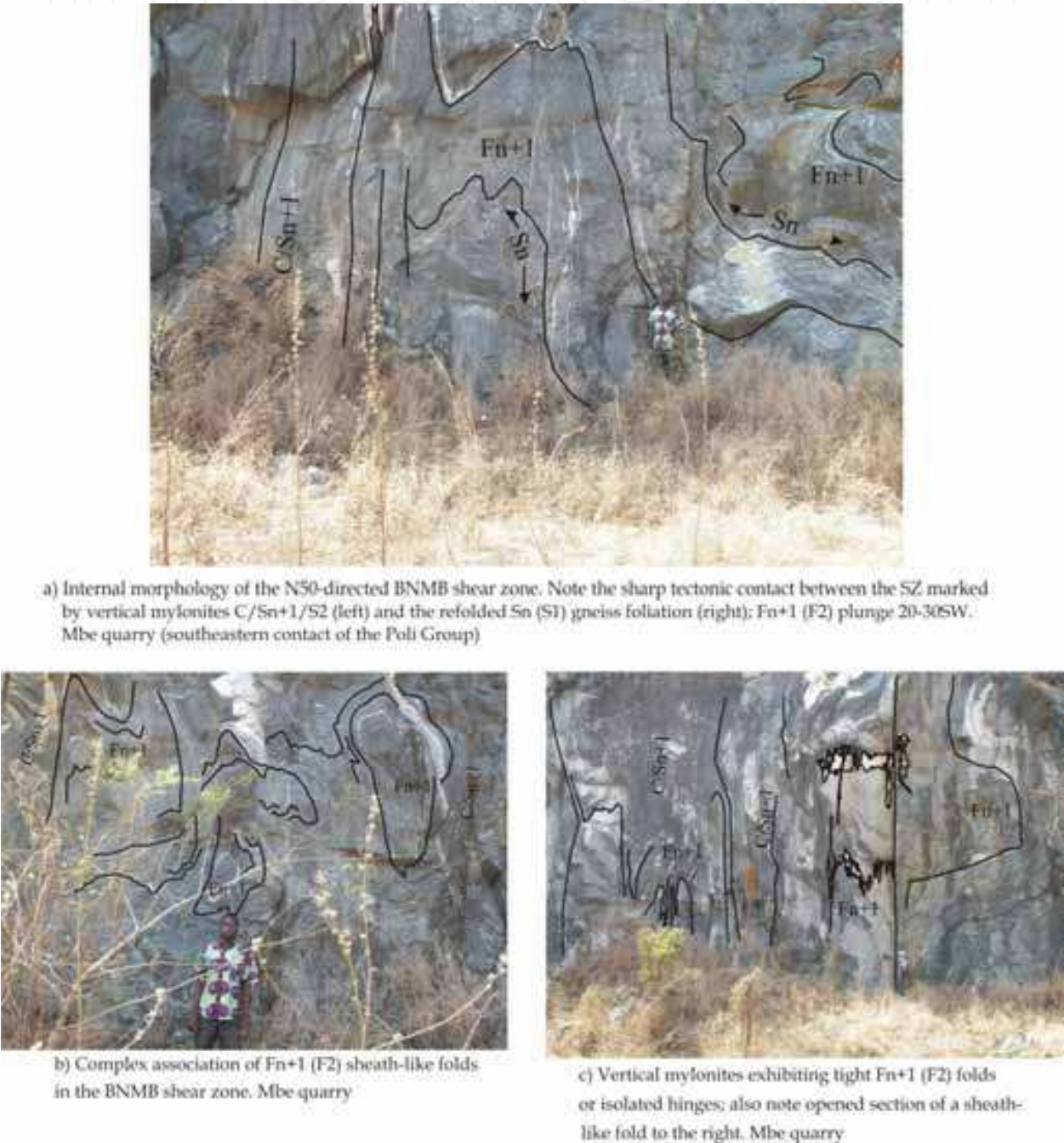
Fig. 5. Internal structure of the BNMB shear zone (Mbe quarry, Northern Cameroon)

porphyroclasts of feldspar, C'-type fabrics and asymmetric boudins of quartzo-feldspathic veins. All these markers are consistent with a bulk sinistral shear movement associated with a moderate normal component along the shear zone. At the regional scale, the general N50 trend of the foliation shows large scale S-type folds that suggest late clockwise rotation of the mylonite band within potential shear zones striking EW (Ngako et al., 2008). A U-Pb sphene age of 580±11 Ma from a mylonitized hornblende-biotite gneiss in the Mbé area was interpreted as dating the sinistral shear evolution (Toteu et al., 2004).

2.2.2.1.1.2 The Godé-Gormaya Shear Zone (GGSZ) and The Mayo Nolti Shear Zone (MNSZ)

The BSZ and BNMB are cross-cut to the West by the GGSZ and the MNSZ, respectively (Figs. 2). Although differently oriented, these synthetic (secondary) SZ are coeval with the major SZ, as both systems show similar senses of shear movement and similar metamorphic evolution. Secondary SZ are almost parallel to N-S batholiths represented by pre-, syn- and late-tectonic intrusions oblique to the major shear zones. The GGSZ shows the most complex structure among this generation.

It is outlined by an intensely deformed meridian belt which intersects with the Balché mylonite fan to the West (Fig. 2). It shows a right-lateral stepping due to segmentation by the Vallée des Roniers (VRSZ) and the Demsa (DSZ) shear zones. In the Godé segment, the Balché mylonites have been variably transposed into N-S direction parallel to small scale meridian SZ, in the amphibolite and greenschist facies, respectively (Toteu et al., 1991). In the Gormaya segment, an E-W cross-section enables define two metamorphic and structural zones: a western garnet-biotite zone (gneisses and migmatites) and an eastern epidote-chlorite zone overprinting the former. These zones exhibit different directions of mineral lineation, meridian in the garnet-biotite and E-W in the epidote-chlorite zones. Kinematic markers in the gneisses and migmatites are typical Z-type sigmoid foliation, compatible with sinistral shear movement, whereas the epidote-chlorite zone exhibits SΛC-type markers (Berthé et al., 1979) indicating a down-slip normal-shear movement. Both, S and C planes in the garnet-biotite zone are coeval with the migmatization, suggesting they were formed during a progressive shear evolution, according to the model of Brun and Choukroune (1981). The superimposition of NS bands of epidote-chlorite upon garnet-biotite mylonites in the Gormaya and Godé segments and their association with EW steep plunging and NS sub-horizontal lineations respectively, suggest successive compressional and extensional evolution of these parallel structures and associated metamorphic zones.

2.2.2.1.1.3 The Sanaga Shear zone

The Sanaga Shear Zone is a major crustal ductile fault identified by remote sensing technique (Dumont, 1986). This shear zone strikes N70°E and likely extends into the Central African Republic. In the Lom region, it intersects with N40 sinistral en-echelon shear zones interpreted as coeval with a pull-apart basin (Ngako et al. 2003) and the deposition of the Lom Group. They mark a step-over between the Sanaga shear zone and the Bouzoum-Ndélé fault which likely represents its eastern equivalent reactivated during Cretaceous in Central African Republic. Deposition of the Lom Group bracketed between 600 and 613 Ma (Toteu et al., 2006) probably dates the sinistral wrench movement in the Lom region.

2.2.2.2 Right lateral wrench movement (ca 585-540 Ma).

The Cameroon domain was dextrally rotated during the last Pan-African tectonic event. Rotation was mostly recorded by shear movements in the CCSZ, but also in northern

Cameroon by E-W directed shear zones including: the 'Vallée des Roniers Shear Zone', the 'Demsa Shear Zone (Fig. 2) and potential shear zones defined by S-type foliation trends in the Mbé region.

2.2.2.2.1 The northern Cameroon dextral Shear Zones

In the Poli region (Fig. 2), the 'Vallée des Roniers' (VRSZ) and the 'Demsa' Shear Zones (DSZ) are coeval with down-slip movements parallel to the Godé and Gormaya segments; both E-W and N-S mylonites determine a complex transtensive system formed in the greenschist facies characterized by chlorite-epidote paragenesis. These shear zones seem to be coeval with the Z-shaped rotation of the synform and antiform axis in the Poli region, associated with NS crenulations cleavage Sn+2/S3 (Fig. 6). Rb-Sr ages at 540-538 Ma (Bessoles & Trompette 1980, and the biotite Rb-Sr ages therein quoted) obtained in the Gouna massifs give a rough age approximation of this late tectonic event in the Poli region.
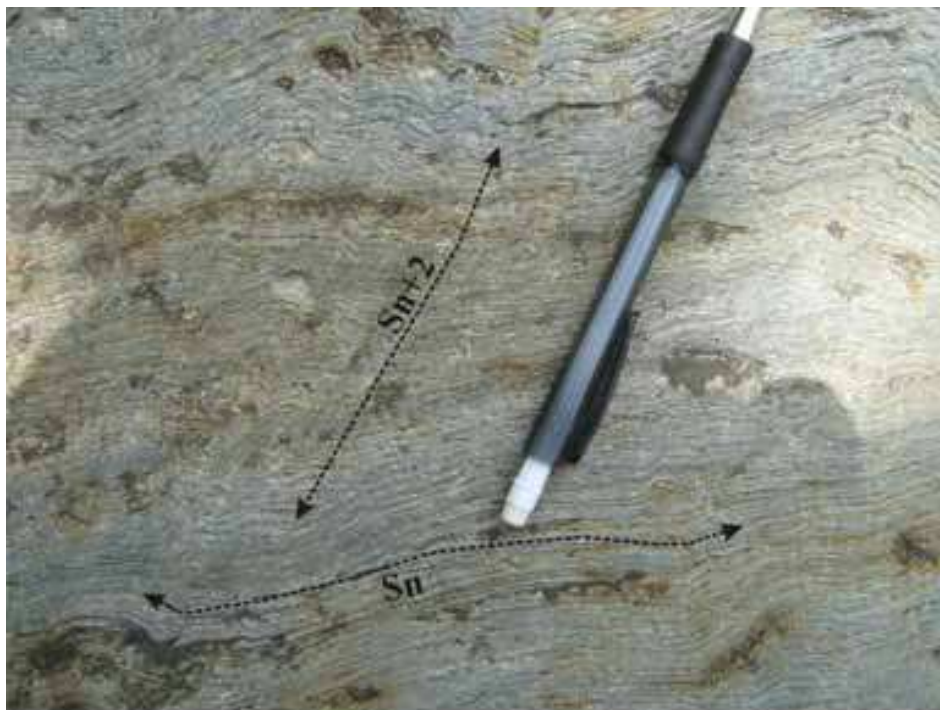

Fig. 6. Crenulation cleavage associated to Late Pan-African folding (Fn+2 or F3) in northern Cameroon (Poli Group)

In the Mbé area (Fig. 2), foliation strikes of the BNMB shear zone show S-type geometry compatible with dextral shear movement (Ngako et al., 2008). These shear zones occurred under amphibolite to greenschist facies metamorphic conditions characterized by biotite ± amphibole ± chlorite ± muscovite ± epidote ± albite.

2.2.2.2.2 The Central Cameroon Shear Zone (CCSZ)

The CCSZ is a N70°E striking major crustal structure parallel to the Sanaga fault and extending from the Soudan region into NE Brazil. It defines a fan-geometry in central Cameroon, due to its interaction with N40°E directed shear zone system (Ngako et al., 2003). Most works in Cameroon and NE Brazil define the CCSZ and correlative extensions as a dextral shear zone (Ngako et al., 1991; Neves & Mariano, 1999; Njanko et al., 2006; Njonfang et al., 2006; Nzenti et al., 2006). However, recent works in Cameroon have also reported the

occurrence of sinistral shear sense indicators associated to the same movement direction as that revealed by the dextral shear markers (Ngako et al., 2003; Njonfang et al., 2006), suggesting a more complex kinematic evolution of the CCSZ. Else, superimposition of opposite sense of shear movement at constant direction (Wenberg, 1996) has been debated in the Achankovil shear zone, southern India (Ishii et al., 2006) and reassessed (Rajesh & Chetty, 2006) through an integrated approach including remote sensing data, shaded relief topo-maps and detail field study, in terms of an initial non-coaxial deformation reactivated and superimposed by opposite kinematics. A Similar evolution could be applied to the CCSZ as already proposed by Njonfang et al. (2006). P-T conditions along the CCSZ were estimated at 3.7-5.7 kb and 738-800°C (Njonfang et al., 1998) and are consistent with the absence or scarcity of actinolite and actinolitic hornblende, symptomatic of greenschist facies, within the mylonitic zones (Njonfang et al., 1998, 2006; Njanko et al., 2006). At the regional level, the NW-SE stress direction coeval with the dextral shear evolution of the CCSZ is compatible with the N-S to NNE-SSW direction of large-scale upright open folds mostly reported in the Yaoundé Group where they show horizontal to northward gentle plunging axis (Mvondo et al., 2003) and in the Meiganga region (Ganwa, 2005).

3. Summary of tectonic evolution in the Cameroon domain- Conclusion

The Cameroon domain recorded three major tectonic events during Pan-African evolution (Fig. 7). Crustal thickening generated southward thrust zones that resulted in an initial burial of the Yaoundé Neoproterozoic Group at the base of an overlying crust situated to the North (Fig. 7b); HP-HT granulites coeval with this early evolution were subsequently exhumed and over-thrust onto the Congo craton, during the late stages of the thrust evolution (Fig. 7c). During the post-collisional history, this complex nappe system was differentiated into two main structural units: a northern unit intensely cross-cut and variably rotated by and parallel to deep lithospheric shear zones, and a southern unit exhibiting huge nappes in their original position striking parallel to the tectonic contact with the Congo craton (Fig. 7d). The regional main stress direction during crustal thickening and subsequent sinistral wrench movement was N-S to NNE-SSW across the belt, and almost remained constant between 630 and 585 Ma, but completely changed into a NW-SE direction during the regional dextral shear movement, between 585 and 538 Ma. The resulting regional strain field shows marked NNE-SSW finite trends outlined by the N-S orientation of synthetic SZ and syn- to late-tectonic intrusions emplaced in extensional zones at right angle with both, the EW thrust zones and subsequent antiform/synform more or less overturned during progressive evolution (Fig. 7b, c and d). The CCSZ and the Sanaga fault mark a major tectonic boundary between these units and probably recorded a complex kinematic history.

4. Regional and pre-drift correlations: discussion

4.1 The Trans-Sahara - Nigeria domain

This domain is characterized by a polycyclic basement flanked to the West and to the East by the Pharusian-Dahomeyan and the Tirririne belts, respectively (Fig. 1). These belts belong to an active margin setting and suggest, as in the Poli region, a nearby inter-plates boundary, here marked by the ophiolites in Aïr (Cosson et al., 1987; Black et al., 1994). The Trans-Sahara-Nigeria domain (Fig. 8) includes dextral submeridian and NE-SW synthetic
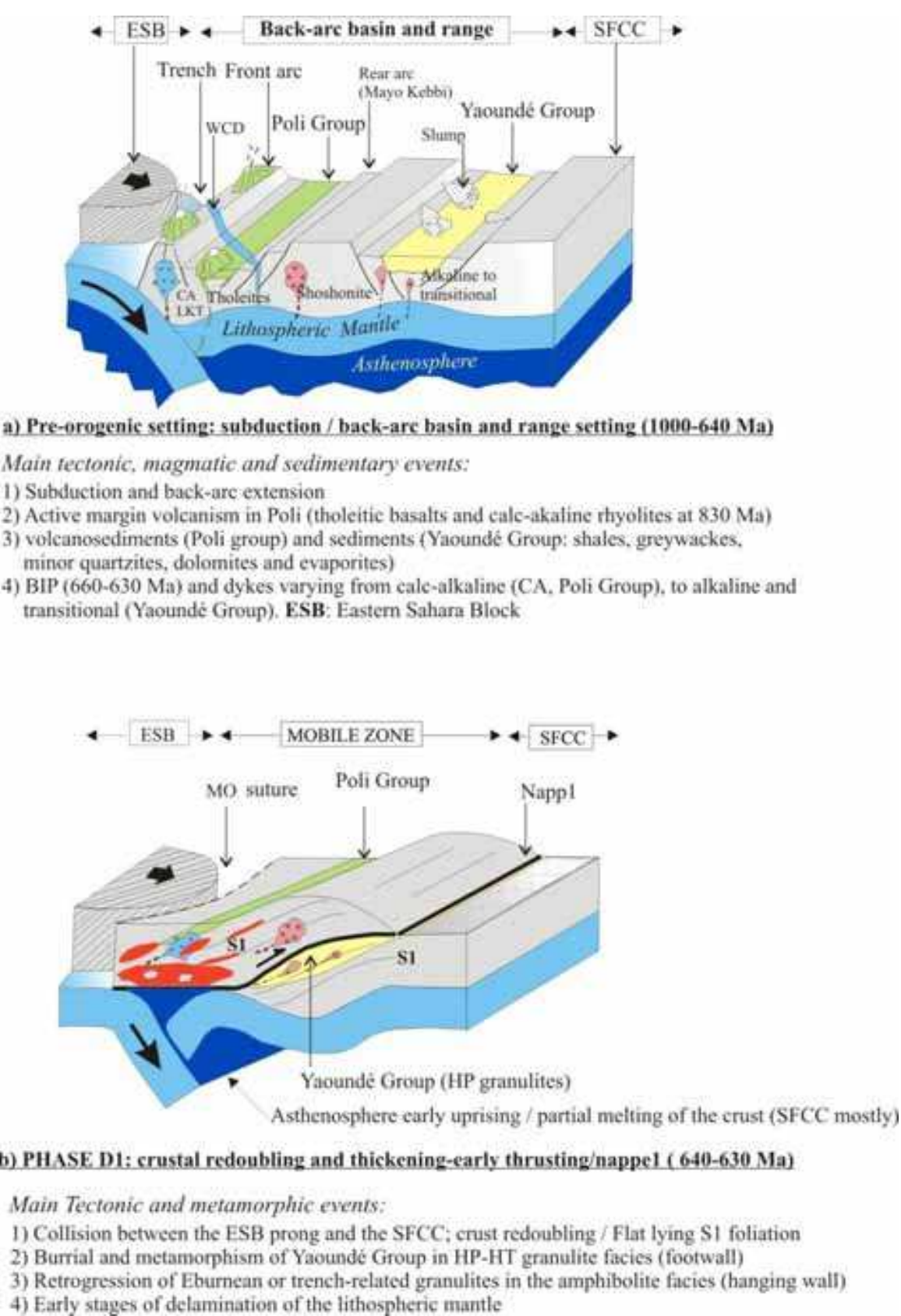
a) Pre-orogenic setting: subduction / back-arc basin and range setting (1000-640 Ma)

Main tectonic, magmatic and sedimentary events:

1) Subduction and back-arc extension
2) Active margin volcanism in Poli (tholeitic basalts and calc-akaline rhyolites at 830 Ma)
3) volcanosediments (Poli group) and sediments (Yaoundé Group: shales, greywackes, minor quartzites, dolomites and evaporites)
4) BIP (660-630 Ma) and dykes varying from calc-alkaline (CA, Poli Group), to alkaline and transitional (Yaoundé Group). **ESB**: Eastern Sahara Block

b) PHASE D1: crustal redoubling and thickening-early thrusting/nappe1 (640-630 Ma)

Main Tectonic and metamorphic events:

1) Collision between the ESB prong and the SFCC; crust redoubling / Flat lying S1 foliation
2) Burrial and metamorphism of Yaoundé Group in HP-HT granulite facies (footwall)
3) Retrogression of Eburnean or trench-related granulites in the amphibolite facies (hanging wall)
4) Early stages of delamination of the lithospheric mantle

Fig. 7. (start). Block diagram summarizing the tectonic evolution of the Cameroon domain and the northwestern regions

c) PHASE D2: crustal shortening and thickening-upright to recline folds/nappe2 (around 600 Ma)

Main tectonic and metamorphic events:

1) Horizontal shortening (F2 upright to recline), thrusting and exhumation of Yaoundé granulites and Ultra Mafic fragments derived from upper mantle along deep listric faults (Thrusting combines pur and simple shear deformation).
2) Retrogression of the Yaoundé HP-HT granulites and widespread migmatization
3) Increasing delamination of lithospheric mantle and uprise of hot asthenosphere against the crust due to indentation.

d) PHASE D3 or late-D2: Conjugate wrench movements at the prong front (585-580 Ma)

Main tectonic and metamorphic events:

1) Wrench movements following penetration of the prong / Lom pull-apart basin
2) Advanced delamination of lithospheric mantle due to indentation
3) Widespread melting and granitization of the crust causing dismembering of the ESB, the active margin, reactivated basement and earlier Pan-African structures. D4 (or D3) dextral shear along the major Pernambuco-CCSZ due to prominent active role of the WACis not represented.

Fig. 7 (end). Block diagram summarizing the tectonic evolution of the Cameroon domain and the northwestern regions

shear zones. All these shear zones usually cross-cut earlier fold and thrust zones, and both structures are diversely interpreted, either as coeval (Caby, 1989; Caby & Boesse, 2001) or not (Ferré et al., 2002).

The Ifewara-Iwaraja Shear Zone (IISZ, Fig. 8) is coeval with NNE verging thrust zone and its evolution has been correlated with that of wrench and thrust zones in the Hoggar (Caby, 1989; Caby & Boesse, 2001) which age ranges from 614 to 629 Ma (Bertrand et al., 1986). Flat-lying migmatites in the Okene region are folded by NE verging anticline coeval with the thrust zones; they show parallel charnockitic veins sometimes exhibiting stygmatic folds. According to the charnockitization age in western Nigeria (U-Pb zircon ages by Tubosun et al., 1984), the early thrust evolution in the Okene region could be situated between 634 and 620 Ma. Therefore, wrench and thrust evolution in western Nigeria is constrained between 634 and 620 Ma and its evolution was controlled by the NNE-SSW stress direction as in the Cameroon domain.

The Pambegua-Bauchi shear zones (PBSZ, Fig. 8), in Central Nigeria (Ferré et al., 2002) represent NNE-SSW synthetics to the NS system. U-Pb dating of zircons from granites and migmatites associated with the thrust and shear zones yielded average ages of 615 Ma and 585 Ma, which were approximated to the ages of thrust and wrench evolution respectively (Ferré et al., 1998, 2002) as in Cameroon.
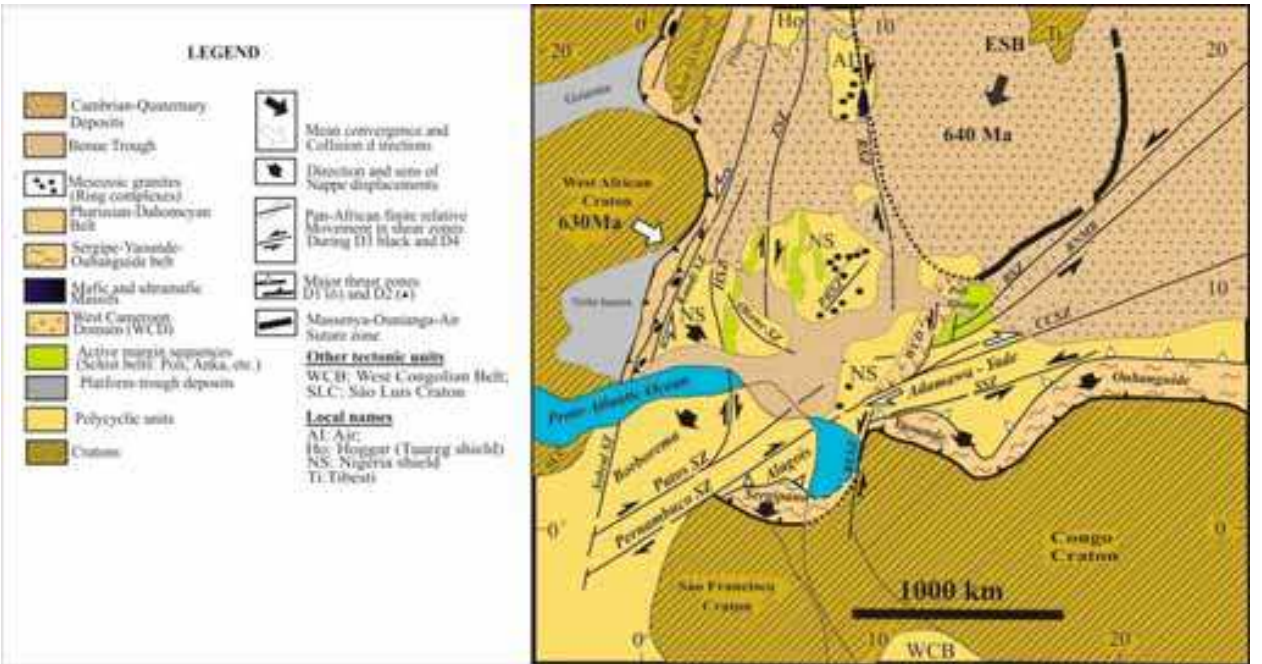
Fig. 8. Pan-African-Brasiliano shear zones and kinematics in pre-drift reconstruction

4.2 The Brasiliano domain

The geology and structure of the Brasiliano domain is summarized in Trompette (1994). Two main geotectonic units are here defined: the Borborema province which represents an old Paleoproterozoic basement reactivated during the Brasiliano orogeny and including metasedimentary belts, and the Canudo-Sergipe (or Sergipano) Neoproterozoic Group overriding the São Francisco Craton to the South (Fig. 8). The Borborema province includes two sets of shear zones: the Cearà-type SZ directed N-S, and the Pernambuco and Patos SZ, E-W-directed. The Patos and N-S branches are interpreted as forming a transpressive dextral

shear zone with duplexes (Corsini et al., 1996), whereas the Pernambuco SZ represents a major structural boundary between the N-S Cearà-type and E-W Sergipano belts.

Tentative correlation of NE-Brazil with its African counterpart (Caby, 1989; Trompette, 1994) shows a good structural fit between the Cearà-type and the Western Nigeria schist belts (Isseyin and Ife), in the one hand, and between the Sergipano and the Yaoundé-Oubanguide Groups, in the other hand; the Patos and Central Cameroon SZ are recognized as structural equivalents (Neves & Mariano, 1999), whereas the Cearà-type SZ are correlated with the trans-Saharan SZ (Caby, 1989). In Brazil, these shear zones are associated to early and late-tectonic transcurrent plutons which ages are bracketed between 600-580 Ma, and 575-565 Ma, respectively (Neves et al., 2004; Souza et al., 2006); both age groups may be correlated with the sinistral and dextral shear evolutions in the Cameroon domain. However, NE-SW sinistral shear zones and respective NS synthetics in northern Cameroon have no equivalent in NE-Brazil. We suggest that the Trans-Sahara- Nigeria – NE Brazil Shear zones in the one hand and the Cameroon-Oubanguides Shear zones in the other hand form a conjugate shear zone system at global scale (Fig.8).

5. The collision and plates amalgamation model-Conclusion

Although based on imprecise data in some cases, correlation of the tectonic events throughout the Pan-African domains and respective kinematics allows determination of a regional strain field compatible with the evolution of a tectonic indent that was progressively formed in northwestern Cameroon between 640 and 580 Ma, during the collision and post-collision evolutions. Indent-related SZ in both western (Trans-Sahara-Nigeria-NE Brazil) and eastern provinces (Cameroon-Oubanguide) were overprinted by right lateral shear movements during a late clockwise rotation of the Cameroon and northwestern domains, indicating a still active collision at the eastern border of the WAC after indentation. The indent related SZ determine a post-collisional branching network system which geometry is different from that of the original belt striking EW. Collision in the Dahomeyan-Pharusian belt is recorded by the early ultra-HP metamorphism between ca 625 Ma (^{40}Ar-^{39}Ar ages on phengite, Jahn et al., 2001) and 633 Ma (^{40}Ar-^{39}Ar ages on muscovite, Attoh et al., 1997), and is almost close to the syn-collisional evolution in northwestern Cameroon, whereas exhumation of the suture zone and nappe stacking at the eastern border of the WAC, dated at ca 590 Ma (^{40}Ar-^{39}Ar ages on muscovite and hornblende, Attoh et al., 1997), coincides with the age of exhumation and over-thrusting of HP-HT granulites onto the SFCC.

In summary, a three-plate collision model involving three major landmasses can be proposed for the Pan-African tectonic evolution of the Trans-Saharan-Central African /CAFB and Brasiliano western Gondwana belts. The model includes: the SFCC, the eastern Saharan block (ESB), and the WAC (Fig. 7 and 8). Collision in the north-south direction involved ESB and the northern margin of the SFCC originally differentiated into a basin and range province (probably during back arc extension related to subduction, Fig. 7a). This collision generated an indent (Fig. 7b and Fig. 8) and intense deformation in the Cameroon and north-western domains, following penetration of the Saharan rigid prong into the SFCC active margin between 640 and 580 Ma. Successive tectonic events recorded in this active margin involved: i) crustal thickening ii) left- and right-lateral conjugate wrench movements (indent), and iii) right-lateral wrench movements in the N70 to EW direction. These structural and kinematic data show that, although collision between the Trans-Sahara active

margin and the WAC started at ca 630 Ma, deformation in north-western Cameroon was mostly controlled by a NNE-SSW stress direction until ca 590 Ma. Further deformation in this domain is recorded by a regional clockwise rotation compatible with a NW-SE stress direction suggesting that the late tectonic event was the only one controlled by the prominent active role of the WAC.

Tectonic indentation requires two major conditions to operate: (1) indenter should be rigid and stronger than indented margin. Considerations to this rheological aspect suggest that active margins should be weaker than passive margins, as particularly submitted to intense seismicity and volcanism during subduction; (2) volume constrains during indentation requires that the denser lithospheric mantle be separated from indenter to enable this one penetrate into the opposite margin. In addition, penetration of indenter would induce differential shortening between continental crust (lighter and deformable) and lithospheric mantle (rigid and denser) in the indented plate causing local delamination of the lithospheric mantle (Fig. 7b, c, d). These fundamental tectonic processes suggest probable ascent of massive volumes of the asthenosphere against the crust, causing large scale melting at the frontal zone of the amalgamating plates. The abundant crustal melting and widespread occurrence of batholiths intrusions that caused intense reactivation and partial dismembering of the colliding plates in north-western Cameroon may be explained by these processes. Increasing metamorphic isograds classically advocated to generate partial melting during thickening would not alone explain these intense and widespread phenomenons, as they would be characterized by a relatively low intensity and apparent regional zoning. The western Gondwana new tectonic model highlights the importance of the boundary geometry of colliding plates, in generating special tectonic processes likely to cause local inversion of the mantle- asthenosphere structure and associated thermal gradients; the absence of apparent belt polarity and zoning in the Gondwana collisional settings would be linked to the presence of a rigid prong. Dismembering of the ESB prong and northern extension of the SFCC during collision may account for these particular processes. Presently, these marginal zones mostly exhibit a marked Pan-African imprint and more detail studies including isotopic and geophysical studies are necessary to enable more precise reconstruction of the respective crustal evolutions.

6. The Post Pan-African history and inferences to plate destruction

The Post Pan-African history in western Gondwana involves sedimentary and magmatic events whose relationships with global tectonics are still not completely understood. This history relates to the Paleozoic, Mesozoic and Tertiary events; it interferes with the breaking of the western Gondwana and subsequent opening of the Atlantic Ocean in the Barremian (Brunet et al., 1988).

6.1 Pan-African molasses

Eroded material identified as Pan-African molasses are found in the belt adjacent foreland basins (e.g. Estancia Group, Dja Group, Proche-Tenere Group, etc.), and within-belt Paleozoic grabens (Trompette, 1994). The Mangbei-type semi-grabens in northern Cameroon (Balche, Nigba, etc.), formed during late Pan-African transtensional movements, are typically located at the intersections between NS secondary and EW shear zones. Main lithologic units in these grabens include: sandstones, conglomerates and continental tholeites represented by acidic, intermediate and basic lavas (Béa et al., 1990).

6.2 The Paleozoic to Quaternary evolution

The Paleozoic to Quaternary alkaline magmatism in Niger, Nigeria and Cameroon, and the associated basins and swells represent one of the most significant and illustrative examples of the post Pan-African evolution in western Gondwana.
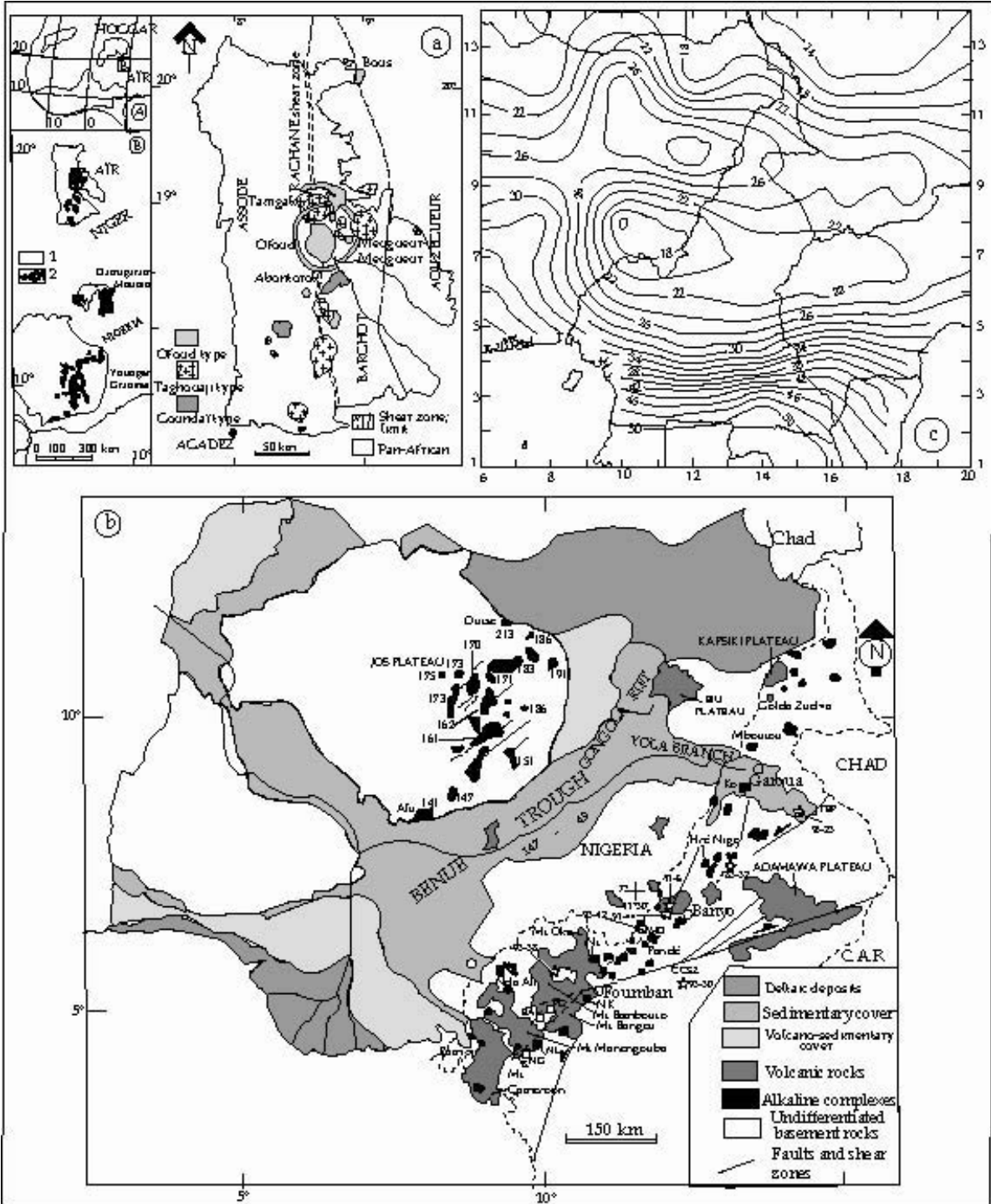

Fig. 9. Phanerozoic major lithospheric structures in Central-West Africa: a) the Air-Damagaram NS-directed magmatic trends; b) The Nigeria (Jos Plateau)-Benue-CL N50-directed magmatic trends, c) Map of crustal thickness in Central Africa based on gravity data (after Poudjom Djomani et al., 1995)

6.2.1 Main magmatic provinces and magmatic activity

A magmatic province is here defined as a broad geographic area (linear or not), characterized by intrusive and/or volcanic bodies, the ages of which approximately correspond to the same geological period, namely Ordovician–Devonian (480-400 Ma), Carboniferous (330-260 Ma), Triassic-Jurassic (215-140 Ma), Cretaceous (147-106 Ma) and Tertiary (73-30 Ma), though age overlapping is reported between some neighboring provinces.

6.2.1.1 The Niger-Nigeria Paleozoic to Mesozoic Super Province

The Niger-Nigeria super province comprises from north to south, the Aïr anorogenic magmatic province (N. Niger), the Damagaram-Mounio province (S. Niger) and the Jos Plateau or 'Younger Granite' province of Nigeria (Fig.9a, inset). A general review of the different types of Paleozoic ring complexes in the Aïr is given by Demaiffe et al. (1991), Moreau et al. (1991, 1994) and Demaiffe & Moreau (1996). The authors recognized 28 complexes among which the largest cone sheet in the world (the Meugueur-Meugueur, 65 km in diameter) and one of the smallest intrusions (Tagueï, 0.8 km in diameter). Most of the intrusions have a circular shape, but some are elliptical or semi-circular. They have been divided into three main types (Fig. 9a) (Moreau et al., 1991; Demaiffe et al., 1991): 1) the Taghouaji type (18 complexes) is composed mainly of alkaline and peralkaline syenite and granite, with or without associated metaluminous granites; 2) the Goundaï type (3 complexes) is composed mainly of acid volcanic rocks (rhyolitic tuffs and ignimbrites) with quartz syenite ring dykes; 3) the Ofoud type (7 complexes) is characterized by a large proportion of basic rocks varying from troctolites and leucogabbros to true anorthosites, intruded by mildly to peralkaline syenites and granites.

In the Younger Granite province of Nigeria, over 50 intrusions forming a series of high level anorogenic complexes have been recognized (Badejoko, 1986; Orajaka, 1986). These circular or elliptical intrusions have an average diameter of 10-25 km. Each of the ring complexes began as a chain of volcanoes. Volcanic rocks commonly occur, especially in the northernmost complexes. Basic intrusive rocks represent less than 1% of the total area of the province (against 40-80% in the Aïr) and include monzonites and monzogabbros (basaltic lavas are more common). Anorthosites occur only as xenoliths in a doleritic dyke near Jos. There are several distinctive granite types (Kinnaird, 1985): i) peralkaline granites and related syenites (with alkali or calcic amphibole); ii) peraluminous biotite alkali feldspar granites and biotite syenogranites; iii) metaluminous fayalite and hornblende-bearing granites and porphyries with amphibole or biotite.

6.2.1.2 The Benue Trough

The magmatic province of the BT constitutes a spatial link between the alkaline to peralkaline province of Nigeria to the north and the CL to the south (Fig.9b). A detail account of its petrology and geochemistry can be found in Baudin (1991) and its main characteristics in Maluski et al. (1995) and Coulon et al. (1996). Two principal magmatic domains are recognized, northern and southern Benue. In the northern domain, magmatism is characterized by transitional alkaline basalts and transitional tholeiitic basalts. Acidic magmatism (rhyolites and granophyres) of peralkaline nature is also present. In the southern Benue, several magmatic districts exhibit alkaline or tholeiitic affinities. Alkaline rocks include basalts, dolerites, rhyolites, trachytes, phonolites, phonotephrites, tephriphonolites, camptonites and nepheline syenites. Only doleritic sills display a clear mineralogical tholeiitic affinity and correspond chemically to quartz tholeiites.

6.2.1.3 The Cameroon Line

The CL, made up of an oceanic (Annobon, São Tomé, Principé and Bioko) and a continental (Mt. Etindé, Mt. Cameroon, Mt. Manengouba, Mt. Bambouto, Mt. Oku, Ngaoundéré plateau, Bui plateau and Mt. Mandara) sectors, has been active since the Cenozoic and is currently defined by an almost SW-NE geological lineament (mean value: N30°E). Its activity includes emplacement of plutonic complexes in the continental sector (more than 60) and volcanic eruptions (Fig. 9b). The plutonic complexes are small in size (mostly 5-10 km in diameter) and except for 4 complexes in north and southwest Cameroon, are mainly constituted of granites or syenites, to which subordinate intermediate and basic rocks are sometimes associated. Volcanic rocks are commonly associated with the plutonic rocks, the whole being referred to as plutonic-volcanic complexes. The Mboutou, Kokoumi and Nigo complexes in north Cameroon comprise basic rocks (Déruelle et al., 1991; Ngako et al., 2006). The Ntumbaw complex in NW Cameroon (Déruelle et al., 1991) contains predominantly intermediate rocks. Syenites are mostly saturated and granites over-saturated, both displaying mineralogical and geochemical characteristics of alkaline to peralkaline rocks. The Kokoumi complex is entirely undersaturated with a gabbro–nepheline monzosyenite - nepheline syenite series. It is also particular in that the plutonic series is cut by lamprophyric dykes (Ngounouno et al., 2001).

Volcanic rocks are more varied mostly undersaturated in the oceanic part and undersaturated to oversaturated in the continental part. At the ocean-continent boundary zone, Bioko and Mt. Cameroon are mainly basaltic. Etindé, located to the intermediate southwestern flank of Mt. Cameroon is made up entirely of undersaturated lavas (Nkoumbou et al., 1995). The other continental volcanoes display either a typical bimodal series (only basic and felsic terms) or a complete series (basic to felsic with few intermediate terms) (Njonfang et al., 2010 in press and references therein). Basic lavas comprise basanites, alkali basalts and hawaiites; intermediate lavas include mugearites and benmoreites and felsic ones comprise trachytes, phonolites and/or rhyolites (Kagou Dongmo et al., 2010 and references therein; Kamgang et al., 2010; Njonfang et al., 2010). Data from the oceanic sector of the CL (Déruelle et al., 1991 and references therein; Lee et al., 1994) indicate basanite to hy-normative basalts, tristanites and trachytes in Annobon; basalts to trachytes and phonolites with no compositional gap in São Tomé; nephelinites, basanites, tristanites, trachyphonolites, phonolites and alkali basalts in Principé and basanites to hy-basalts in Bioko. In Principé, the oldest rocks (31 Ma) are basal hyaloclastite breccias that contain fragments of fresh tholeiite (Fitton & Dunlop, 1985). Aka et al. (2004) noted a geographic control on the distribution of ^{3}He/^{4}He ratios along the CL, with high-μ OIB-like values on the ocean-continent boundary zone (Bioko, Mt. Cameroon and Etinde) increasing to mantle (MORB-like) values in its oceanic (towards Annobon) and continental (towards Ngaoundéré) terminals. Even though a review of the CL volcanism by Déruelle et al. (1991) suggests that it is entirely alkaline in nature, some transitional affinities have recently been described in the Mbam, Bangou, Bambouto and Oku volcanic centers in the west and northwest Cameroon (Marzoli et al., 2000; Fosso et al., 2005; Moundi et al., 2007). Some mafic lavas of the CL are rich in ultramafic xenoliths (Lee et al., 1996; Aka et al., 2004). These occur in both the continental sector as in Lake Nyos (Nana et al., 2001; Temdjim et al., 2004), the Kapsiki plateau (Ngounouno et al., 2008) and the Mount Cameroon (Wandji et al., 2009) and in the oceanic sector as in São Tomé (Caldeira & Munhá, 2002).

6.2.2 Spatio-temporal evolution of magmatic activity

On the basis of ages decreasing from the Aïr ring complexes, north of Niger (480-400 Ma) to the Younger Granites of Nigeria in the south (215-140 Ma) through the Damagaram, south of Niger (330-260 Ma), the Niger–Nigeria large magmatic province has been defined as a unique feature in the world of practically continuous within plate anorogenic volcanism and plutonism, with progressive southward shift of centres of magmatic activity (Bowden & Karche, 1984). At the scale of the Aïr province alone, the ages decrease from 487 Ma in the north to 407 Ma in the south described by Bowden & Karche (1984) was not confirmed by new radiometric data (Rb/Sr method) on the same sample powders by Moreau et al. (1994) . Instead the new results show that the emplacement of the Aïr ring complexes took place within a very short time at 407 ± 8 Ma, close to the Silurian-Devonian boundary or the lowest Early Devonian. In Nigeria, the ages of the Younger Granites show that major local migration of magmatic activity was concentrated along two ENE-WSW linear zones at least, from Dutse (213 Ma) in the north, to Afu (141 Ma) in the south (Fig. 9b).

A detailed chronology of emplacement of volcanic rocks of the BT has been established using the Ar/Ar method and the following magmatic evolution is revealed (Maluski et al., 1995). (1) During the Late Jurassic to Albian period (147-106 Ma), magmatism probably occurred in the whole basin. It is particularly expressed in the northern Benue where it is represented by alkaline transitional basalts and associated peralkaline rhyolites (bimodal volcanism) and by tholeiitic transitional basalts. (2) Between 97 and 81 Ma, magmatism was concentrated in the southern Benue, was exclusively alkaline, and predominantly intrusive. (3) During the period 68-49 Ma, the first magmatic products, also restricted to the southern Benue, were alkaline and the last ones tholeiitic. As in the Aïr province (e.g. Moreau et al., 1994), no clear time-space migration of magmatism in the BT is apparent.

Previous radiometric data (Rb/Sr and K/Ar methods) for the anorogenic plutonic complexes of the CL indicate that their emplacement occurred from the Paleocene (*ca* 67 Ma) to the Oligocene (*ca* 30 Ma). The oldest age was obtained on the Golda Zuelva granite in the north, and the youngest on the Mt. Bana granite in the west (Lasserre, 1978). However, the Nkogam and Mboutou complexes in the west and north gave 66 and 60 Ma respectively (Lasserre, 1978; Caen-Vachette et al., 1987), pointing to the lack of time-space migration of plutonism. This conclusion is corroborated by the ages recently obtained for the Kokoumi complex southwest of Mboutou (39 Ma) and for the Hossere Nigo west of Adamawa plateau (65 Ma) (Ngounouno et al., 2001; Kamdem et al., 2002; Montigny et al., 2004).

New K/Ar and Ar/Ar data on volcanic rocks of the CL (Ngako et al., 2006 and reference therein; Moundi et al., 2007; Wandji et al., 2008) show that volcanic activity ranges from Upper Eocene (47 Ma) to the Present and not from Oligocene (30 Ma) as established for the distribution of volcano-capped swells along the line (Burke, 2001). Lee et al. (1994) noted a SW younging of volcanism in the oceanic sector of the CL from Principé (31 Ma) to Pagalu (5 Ma). The oldest volcanic ages (K-Ar) so far obtained (46.7 ± 1.1 Ma and 45.5±1.1 Ma) are respectively in an olivine basalt from the Bamoun plateau (Moundi et al., 2007) and the Mbépit rhyolites in the Noun plain (Wandji et al., 2008), next to the Bamoun plateau. The transitional lavas from the Bamoun plateau give a K-Ar age of 51.8±1.2; Ma (Moundi et al., 2007) and those of Mount Bangou, a K-Ar age of 44.5±1 Ma (Fosso et al., 2005). Therefore, as for anorogenic complexes, it is difficult to consider volcanic activity along the whole CL in terms of a steady time-space migration, symptomatic of a mantle plume reference frame as in the Hawaiian Islands.

From the above synthesis, it is seen that alkaline magmatism in West-Central Africa shows a time-space migration marked by ages decreasing from the Silurian-Devonian boundary (407±8 Ma) in the Aïr province (north Niger) through the Younger Granites of Nigeria (213-141 Ma), the BT (147-49 Ma) to the Paleocene-Present activity on the CL. This seems at first sight to result from a single mantle plume. However, the magmatic period of the BT overlaps the period of plutonic magmatism on the CL and also, the ring complexes of Nigeria display roughly two SW-trending lines of decreasing ages. These observations suggest that magmatism in West-Central Africa may instead be the result of an interaction between mantle plume(s) and other important factors such as lithospheric fractures.

6.2.3 Relationship between tectonics and magmatism

6.2.3.1 The Pan-African structural inheritance

Three main structural units characterize the Pan-African basement in western and central Africa (Fig. 8): shear zones, fold zones and thrust zones. Shear zones are the most prominent and represent lithospheric faults. The Aïr basement that was built during the Pan-African orogeny (Black et al., 1994; Liégeois et al., 1994) resulted from the assembly of three main terranes (Assodé, Barghot and Aouzegueur), separated by N-S trending shear-zones or mega-thrusts (Fig. 9a). These shear and thrust zones control: (1) the variation in thickness and/or deformation of the sedimentary cover; (2) the location of basement topographic highs and (3) the location of the magmatic activity (Moreau et al., 1994). The most important of the shear zones, the Raghane mega-shear zone (Fig. 9a) can be observed over a 400 km distance in Aïr and runs for more than 1000 km, as it corresponds to the southern extension of the 8°30' E lineament of the Hoggar (Demaiffe & Moreau, 1996; Abdelsalam et al., 2002). In general, N-S mega-thrust faults were followed by NW-SE trending sinistral wrench faults and by complementary ENE-WSW and NE-SW trending dextral faults. In Nigeria, the major faults are NE-SW to NNE-SSW and ENE-WSW trending dextral wrench faults (Rahaman et al., 1984 and references therein). The distribution of Triassic-Jurassic anorogenic ring complexes in the Jos Plateau defines a sigmoidal megagash geometry with a ENE-WSW mean direction that is probably linked to shear movement along pre-existing ENE-WSW trending wrench faults in the Pan-African basement (Rahaman et al., 1984; Black et al., 1985). This suggests that the Aïr and Younger Granite provinces were not emplaced under the same stress regime (Demaiffe & Moreau, 1996). The BT is a NE-SW trending extensional sedimentary basin (Benkhelil, 1989) considered to be the failed arm of a Cretaceous triple junction, the two other rift arms of which subsequently developed into the South Atlantic Ocean and the Equatorial mega-shear zone (Burke & Dewey, 1974). Opening of the trough has also been attributed to reactivation during Cretaceous-Early Tertiary times of late Pan-African NE trending dextral shear zones (Guiraud & Maurin, 1992). In Cameroon, the basement is affected by a major translithospheric mega-shear that extends ENE from the Gulf of Guinea, through southern Chad and the Central African Republic into western Sudan. This Central African Shear Zone referred to as the Ngaoundéré or Foumban lineament (Browne & Fairhead, 1983) or the Central Cameroon Shear Zone (Ngako et al., 1991 and reference therein), is a dextral shear that was formed during the Pan-African orogeny and is delineated by broad mylonite zones. The Patos and Pernambuco-Adamawa branches and their N-S relays control the geometry of the BT (Maurin et al., 1986; Guiraud & Maurin, 1992) and the CL respectively (Fig. 8 & 9). Detailed structural studies of some syntectonic Pan-African granitoids in Cameroon show that they are broadly elongated and

aligned NE-SW, consistent with their successive emplacement coeval with acting and oblique sinistral shear zones formed during an earlier deformation phase (Ngako et al., 2008). For example, in the Ngondo complex (1000 km²), the geometry of the internal foliation trajectories and joint orientation suggest that its emplacement was controlled by a N30° sinistral shear zone (Tagne Kamga et al., 1999), a conclusion earlier drawn for the Bandja complex (300 km²) which outcrops in a N30° elliptic sheet (Nguiessi Chankam et al., 1997). In the Biu Plateau (CL), the distribution of volcanic necks appears to be controlled by a N-S alignment of Tertiary faults. The emplacement of Paleocene and Eocene alkali granitic intrusions in Cameroon appears to be similarly fault controlled (Moreau et al., 1987). Indeed, it is partly superimposed on the Central African Shear Zone (Cornachia & Dars, 1983) which is a pre-existing fracture zone (Fig. 8 and 9). It has been suggested that volcanoes in the offshore part of the CL are located at places where the line crosses fracture zones while inland volcanoes are located along structures related to Riedel-style shear zones (see Meyers et al., 1998 and references therein). Fold zones are characterized by Pan-African domes or diapirs of granitoid (calc-alkaline) rocks (Grant, 1978; Ngako, 1999 and references therein). They determine broad areas bounded by the Nigeria and Cameroon shear zones and are dominantly characterized by the occurrence of Paleozoic to Cenozoic ring complexes. Thrust zones (Ball et al., 1984; Jégouzo, 1984; Nédélec et al., 1993; Penaye et al., 1993) characterize the main structures of the Pan-African belt and overlay the Achaean and Eburnean boundary. These zones reveal no post-Pan-African magmatic activity, neither intrusive, nor effusive.

6.2.3.2 Swell-and-basin structures and magmatic provinces

Topographically, the general structures in western and central Africa suggest a long-lived continental extension history, ongoing at least since Ordovician from one magmatic province to the other. These structures are represented either by large African lithospheric domes or swells such as the Hoggar, Aïr, Adamawa, Tibesti, Darfur and the Great Lakes of East Africa (Ebinger et al., 1989; Burke, 2001), or by grabens, such as the BT (Benkhelil, 1989). Domes correspond to high plateaus and mark the early stages of rift evolution. In Aïr, Jallouli (1989) estimated the thickness of the elastic lithosphere to be 20-30 km which is thin for a continental environment, but comparable to what is commonly observed in rift zones. Harley et al. (1996) estimated a particularly thin elastic thickness for the lithosphere in the general region of the CL and Poudjom Djomani et al. (1997) found both crustal thickness and elastic thickness of the lithosphere to be unusually thin in the continental part of the CL. For example, their map of crustal thickness (Fig. 9c) has a minimum value of 18 km at around 7°N, 11.5°E, recently referred to by Burke (2001) as the location of a mantle plume (the '711 plume'). The location of these swells coincides with magmatic provinces of different ages as in Aïr and in the CL. In Cameroon, the four islands of Bioko, Principé, São Tomé and Annobon, the two large seamounts (Burke, 2001) and the four central volcanoes of mounts Cameroon, Manengouba, Bambouto and Oku occupy swells of the CL. They define a 1000-km long SW-NE straight line and display a 'swell and basin' geometry which recalls the horst and graben structure of the whole CL (Déruelle et al., 1991). In West and Central Africa, Guiraud & Maurin (1992) recognize two main phases of rifting separated by a major Aptian (ca 117 Ma) unconformity. (1) The Neocomian-Early Aptian (ca 144-117 Ma) phase that began in the basins of east and northeast Brazil, Gulf of Guinea, south Chad, Sudan, Kenya, north and east Niger, north Egypt and Libya. Late Jurassic magmatic activity appears to precede this rifting phase in northeast Brazil, south Sudan and the BT of Nigeria.

(2) The Middle-Late Aptian-Albian (*ca* 117-98 Ma) phase marked among others by the development of pull-apart basins in an oblique extensional regime from Benue to southern Chad. This is related to strike-slip movements along the Central African Shear Zone (Bosworth, 1992). Magmatic activity in the BT was particularly important during the Cretaceous-Early Tertiary and took place in many phases, contemporaneous with the opening and infilling of the trough (Wilson & Guiraud, 1992). The first phase (Early Cretaceous: 141-106 Ma; Baudin, 1991) is related to the main extensional tectonic regime which affected the trough. During the Tertiary, basaltic magmas were emplaced throughout the entire trough with the greatest concentration in the NE (Wilson & Guiraud, 1992). This Post-Cretaceous extension and volcanism in the Upper Benue corresponds to a period of general stress release after the Santonian or Cretaceous compressional events (Benkhelil, 1989). In general, magmatic activity is predominantly basaltic in the Upper Benue, although rhyolites occur locally. In the Garoua basin, which represents the eastern continuation of the Yola branch of the Upper Benue, the strata are cut by lineaments which may have acted as strike-slip or normal faults. Tertiary-Quaternary magmatism associated with these lineaments occurs as doleritic sills, Paleocene (65-60 Ma) alkaline complexes and Neogene trachy-phonolite necks and dykes (Guiraud et al., 1987). An entirely younger undersaturated anorogenic complex (Kokoumi) belonging to the basin and including a gabbro-nepheline syenite series (39 Ma) and lamprophyre dykes (20.5 Ma) has been studied (Ngounouno et al., 2001).

6.2.4 Continental breaking and possible links with magmatic chains – discussion

From the synthesis above, it appears that (1) There is a time-space link among the magmatic alkaline provinces in West-Central Africa, from 407±8Ma in Aïr (N. Niger) and 330-260Ma in Damagaram-Mounio (S. Niger) to 66 Ma-Present in Cameroon, through 213-141Ma in Jos Plateau (N. Nigeria) and 147-49 Ma in the BT (S. Nigeria). The migration follows an N-S trajectory in the Aïr–Damagaram-Jos provinces, and a NW-SE trajectory in the BT-CL provinces. (2) Only the Aïr province displays a N-S trend of magmatic complexes, the Jos Plateau, BT and CL complexes show three parallel lines rather trending NE–SW. A similar N-S trend followed by a NE-SW one links the N-S East-African Rift System to the NE-SW major igneous lineaments in South Africa (Kinabo et al., 2007, Moore et al., 2008). (3) Each trend is parallel to a shear or fracture zone: N-S Raghane shear zone for the Aïr, NE trending wrench fault for Jos Plateau, NE-trending dextral shear zone for the BT, NE-trending sinistral fault oblique to the Central African Shear Zone or fracture zones directed N70°E for the CL (Fig. 9). (4) Only the ages of the Younger Granites of Nigeria become steadily younger from Dutse (213 Ma) in the NE to Afu (141 Ma) in the SW over a distance of 420 km. (5) There is a great overlap between the third magmatic period in the BT (68-49 Ma) and the ages of anorogenic complexes (66-30 Ma) of the CL, while the beginning of the first magmatic period (147Ma) coincides within analytical error range, with the end of the emplacement of granite complexes of Nigeria (141Ma). An extended discussion on the origin of the magmatic provinces in West Africa, and in the Air-CL line is provided in Ngako et al. (2006) and only summarized in this section.

Following Hieronymus & Bercovici (2000) model, the spreading ridge of the proto Atlantic Ocean during Barremian offers a tentative explanation for the SW-NE Nigeria-BT-CL parallel trends which is susceptible to take into account the whole geometry and structure of the intraplate magmatism in West and Central-Africa. This model predicts island chains

aligned with a deviatorically tensile tectonic stress perpendicular to the ridge; the thin elastic lithosphere near the ridge is subjected to strong deviatorically tensile stress field perpendicular to the ridge axis. Under such conditions the model results in parallel lines of volcanoes perpendicular to the spreading ridge. The model explains the development of non-hotspot and seamount chains in terms of the vulnerability of the lithosphere to magma penetration due to lithospheric stresses and the effects of melting of the conduit walls. Their theory is based on the assumption that (1) transport of magma through the brittle part of the lithosphere occurs via fractures and (2) melt is distributed uniformly at the base of the lithosphere underlain by a superswell. It turns out that an initial perturbation is required in all cases to localize volcanic activity. This initial perturbation may be provided by a change in the tectonic stress field due to plate motion reorganization (which is amplified locally by an inhomogeneity in the lithosphere), the formation of a small sublithospheric melting anomaly or a change in convection. Hieronymus & Bercovici (2000) have finally shown that multiple lines of volcanoes can result from interaction of flexural, membrane and tectonic stresses. Indeed: i) due to tensile membrane stresses, several volcanoes typically form in the space between any two volcanoes of the initial chain; ii) membrane stresses perpendicular to the axis of the ridge also interact with the flexural stresses to generate volcanism away from the axis. This off-axis volcanism eventually forms additional lines of volcanoes parallel to the first one. However, at variance to this scheme, the time-space migration of magmatic lines from Jos Plateau (ca 200 Ma) to the CL (ca 60 Ma) suggests an opening of the Gulf of Guinea spreading ridge from NW to the SE.

The origin of intra-plate magmatism on the African continent (and elsewhere in the world, e.g., Smith & Lewis, 1999) is still a topic of great contention. Some workers (e.g. Wilson & Guiraud, 1992; Lee et al., 1994; Ebinger & Sleep, 1998) link it to the role of mantle plumes. However, most African hotspots have been active since the Cretaceous; thus, to explain the extensive Triassic-Early Jurassic magmatism along the West African and North American margins, Wilson (1997) suggested the location of a pre-Pangea continental break-up 'super plume' axis beneath West Africa. Studies of uplift history, topography and seismic tomography of the African plate and underlying mantle (Lithgow-Bertelloni and Silver, 1998; Begg et al., 2009 and references therein) indicate that southern Africa is underlain by a large-scale buoyant, low seismic velocity structure extending from just above the core-mantle boundary to near the base of the African lithosphere and that the ascent of this material could be feeding many hotspots in Africa (Gurnis et al., 1999). However, based on the fact that all plumes born (as traps) in the last 100 Ma (i.e. Ethiopia-Yemen/Afar) are still quite active, whereas those born between 100 and 140 Ma may be failing while those older than 150 Ma do not in general have an active trace (Duncan & Richards, 1991; Courtillot et al., 1999), it is very difficult to explain the whole Air-CL trend by a simple motion of the plate over one stationary hotspot as in the Hawaiian system. The 1650 km distance stretched by the magmatic provinces following this trend is more than three times the postulated diameter of the St. Helena plume tail (O'Connor & Le Roex, 1992; Wilson, 1992). Burke (2001) also demonstrated that a single plume, dubbed the '711' plume, formed the Nigerian granites, generated a topographic dome at *ca* 140 Ma on which the triple-rift system among which the BT developed, and that the plume was also involved in forming the Cameroon granitic complexes: (i) Between 213 and 141 Ma, the 711 plume generated a 400 km-long line of intrusions as the continent moved over it. (ii) From 140 to 66 Ma, the plume moved *ca* 300 km with respect to the overlying continental lithosphere, having been caught up in the evolution of the Benue rift system (Maluski et al., 1995) rather than forming a line of

intrusions. (iii) Since 66 Ma, the 711 plume has stayed in the same place, close to lat. 7°N and long. 11.5°E, but has been associated with the development of the CL. Though important differences exist between the tectonic models, an agreement appears on the interaction between preexisting Pan-African faults and one or more superswells in Western Africa.

7. General conclusion

The history of western Gondwana includes complex tectonic processes that led to plate's amalgamation and the formation of this supercontinent, and also to the breaking and dismantling of the amalgamated plates that culminated with the opening of the Atlantic Ocean. Unlike the tectonic evolution in most modern collisional belts, plate's amalgamation involved more than two plates converging in different directions and colliding almost simultaneously. Some of these plates like the ESB were completely dismantled by post-collisional processes and can be presently assessed only through their vestiges.

The Gondwana mobile zones exhibit particular features that render their reconstruction complex. However, the present study has shown that the particularly abundant and widespread partial melting and inferred reactivation that partly caused the dismembering of the colliding SFCC-ESB plates may be explained by the tectonic indentation model. Likely, decoupling of the lithospheric mantle from overlying crust as the result of volume constrains and differential shortening of the lighter and deformable crust during indentation has constituted an efficient mechanism to enhance ascent of the asthenosphere against the crust causing large scale pervasive melting and granitization during the building-up of the Gondwanaland.

Phanerozoic evolution of western Gondwana is mostly characterized by continental extension. The genesis and location of swells and basins as well as the related magmatic provinces was mostly controlled by the interaction of superswells with Pan-African fractures. However, it is likely that the classical hotspot evolution model proposed by previous authors interacted with or was relayed by near axis and superswell chains in Nigeria, BT and CL during progressive opening of the Gulf of Guinea in the Cretaceous (Berriasian to Maestrichian). Obviously, the present prominent lithospheric structures in Africa and Brazil have completely obliterated the Neoproterozoic lithospheric ones and only account for the reconstruction of the Phanerozoic history of the western Gondwana.

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Tectonics

Edited by Dr. Damien Closson

ISBN 978-953-307-545-7

Hard cover, 358 pages

Publisher InTech

Published online 28, February, 2011

Published in print edition February, 2011

The term tectonics refers to the study dealing with the forces and displacements that have operated to create structures within the lithosphere. The deformations affecting the Earth's crust are result of the release and the redistribution of energy from Earth's core. The concept of plate tectonics is the chief working principle. Tectonics has application to lunar and planetary studies, whether or not those bodies have active tectonic plate systems. Petroleum and mineral prospecting uses this branch of knowledge as guide. The present book is restricted to the structure and evolution of the terrestrial lithosphere with dominant emphasis on the continents. Thirteen original scientific contributions highlight most recent developments in seven relevant domains: Gondwana history, the tectonics of Europe and the Near East; the tectonics of Siberia; the tectonics of China and its neighbourhood; advanced concepts on plate tectonics are discussed in two articles; in the frame of neotectonics, two investigation techniques are examined; finally, the relation between tectonics and petroleum researches is illustrated in one chapter.

How to reference

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Ngako Vincent and Njonfang Emmanuel (2011). Plates Amalgamation and Plate Destruction, the Western Gondwana History, Tectonics, Dr. Damien Closson (Ed.), ISBN: 978-953-307-545-7, InTech, Available from: http://www.intechopen.com/books/tectonics/plates-amalgamation-and-plate-destruction-the-western-gondwana-history

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