C. R. Geoscience 348 (2016) 572–586

Contents lists available at ScienceDirect

Comptes Rendus Geoscience

www.sciencedirect.com

Review paper

The 2-Ga Eburnean Orogeny in Gabon and the opening of the Francevillian intracratonic basins: A review

Francis Weber [a,*], François Gauthier-Lafaye [b], Hubert Whitechurch [c], Marc Ulrich [c], Abderrazak El Albani [d]

[a] LHYGES – CNRS, 3, rue du Doernel, 67000 Strasbourg, France
[b] LHYGES – CNRS, 14, rue du Petit-Pré, 67800 Hoenheim, France
[c] IPGS, université de Strasbourg, 1, rue Blessig, 67084 Strasbourg cedex, France
[d] Institut IC2MP, UMR 7285 CNRS-INSU, université de Poitiers, 86000 Poitiers, France

ARTICLE INFO

Article history:
Received 28 April 2016
Accepted after revision 10 July 2016
Available online 5 November 2016

Handled by Isabelle Manighetti

Keywords:
Proterozoic
Eburnean orogeny
Francevillian
Gabon
Plate tectonic
Intracratonic basins

ABSTRACT

The Eburnean orogeny in Africa results from the continental collision between the San Francisco and Congolian cratons. The different stages of this orogeny in Gabon are described from the initial rifting of the Archean continent with the crustal melting producing pre-Eburnean migmatites at 2450 Ma, the opening of an ocean. The eastward subduction of the oceanic lithosphere produced eclogites at 2120 Ma and intrusion of calc-alkaline plutons between 2083 and 2040 Ma. The blocking of the subduction by continental collision in the south induced strike-slip motion and the opening of the intracratonic Francevillian pull-apart basins. The thrusting of the units of the Ogooué complex is linked to the rapid uplift of the orogenic root (slab break-off?) and is sealed by the intrusion of the Lecoué granite at 2009 Ma. Our interpretation links the main tectono-metamorphic phases registered in the mobile zone of Ogooué with the sedimentary events in the pull-apart Francevillian basins.

1. Introduction

Late Archean and Paleoproterozoic times are regarded as a period of transition between Archean and Phanerozoic tectonic styles (Cagnard et al., 2011; Cawood et al., 2006; Condie, 1986, 2005; Windley, 1995; Zhao et al., 2002). The Archean style includes accretion with komatiite plumes, short-term subduction within a hotter mantle and tonalite–trondhjemite–granodiorite intrusions resulting from partial fusion of the down-going slab into the upper plate (Gapais et al., 2014; Moyen and Hunen, 2012). The Early Proterozoic (2.5–1.8 Ma) orogenic domains in many part of the world exhibit a fold-thrust tectonic style with ophiolites and HP metamorphism as eclogites comparable to Phanerozoic mountain belts, juxtaposed with large igneous lopolith intrusions known in the Archean cratons (Condie, 2005; Windley, 1995). Examples of such modern orogeny in the Paleoproterozoic are described in Finland (Korja and Heikkinen, 2005), Canada (Cook et al., 1999; White et al., 2002), Western Australia (Cawood and Tyler, 2004), North China craton and the Proterozoic orogens surrounding the Tanzanian craton (Möller et al., 1995), Arabian-Nubian Shield (Kröner, 1985) and southwestern USA (Condie, 1986).

The Eburnean orogeny in western Africa (Gabon, Congo, Cameroon) is considered to be a fold-thrust belt, strictly comparable to the Phanerozoic belt governed by modern Plate Tectonics (Ledru et al., 1994; Lerouge et al., 2006; Thiéblemont et al., 2009a). Indeed, the Ogooué complex in

* Corresponding author.
E-mail addresses: weber.francis@neuf.fr (F. Weber), fgl@unistra.fr (F. Gauthier-Lafaye), hubert.whitechurch@unistra.fr (H. Whitechurch), mulrich@unistra.fr (M. Ulrich), abder.albani@univ-poitiers.fr (A. El Albani).

http://dx.doi.org/10.1016/j.crte.2016.07.003
1631-0713/

Gabon is composed of thrusted units, extending over 200 km, resulting from the continental collision between two Archean cratons: the West Congolian craton to the east and the San Francisco craton to the west.

In Gabon, the Paleoproterozoic terrains outcrop in two distinct areas. On the one hand, the Ogooué Belt, situated between the Ikoy–Ikobé and Ougoulou–Offoué faults, is composed essentially of metasedimentary units, overlying migmatitic units, resulting from low to high degrees of metamorphism, respectively. On the other hand, the Francevillian intracratonic basins of M'Bila, Boué, Franceville, and Okondja, situated to the east of the Ougoulou–Offoué fault, are composed of un- to slightly metamorphosed sediments (Baud, 1954; Choubert, 1954; Cosson, 1956, 1957, 1961; Donot and Weber, 1968, 1969). A 150-km-long strip of Archean formations, forming the Lopé High, separates these two areas (Fig. 1).

The interpretation of the Gabonese Eburnean mountain range differs according to the authors. Feybesse et al. (1998) suggest an intracratonic model to explain the Eburnean orogeny, while Thiéblemont et al. (2009a) developed convincing arguments for a continental collision model. However, their conceptual model does not integrate the history of the intracratonic Francevillian basins.

At the very beginning of the geological survey in the 1950s, geologists, particularly Cosson (1956), suspected that the Ogooué Belt and the Francevillian basin might be related. But it is only during the last decade of the twentieth and the beginning of the twenty-first centuries, thanks to the construction of the "economic road" and of a railway crossing the country, that geological observations could be performed in good conditions, despite dense tropical forest environments. New radiometric datings help to better constrain the events affecting these two domains. The new edition of the geological map of Gabon at the 1/1,000,000 scale (Thiéblemont et al., 2009b), resulting from recent geological surveys, reports all the radiometric ages that have been performed in the Proterozoic rocks of Gabon. This data bank is our reference in the present study (supplementary material, Table S1).

This paper provides a review of the existing data concerning the Eburnean orogeny in Gabon and a new interpretation integrating the events affecting the Ogooué complex and the intracratonic basins.

2. Description of the Proterozoic formations in Gabon

2.1. Proterozoic formations of the Ogooué Belt

The Ogooué belt is limited to the west by the main shear zone of the Ikoy–Ikobé fault and to the east by the Lopé High (Fig. 1a). It represents a now-eroded mountain belt built during the Eburnean orogeny, cartographically covering a surface of 13,000 km^2 corresponding to a volume greater than the HP–LT "Schistes lustrés" in the Alps (Thiéblemont et al., 2009a).

This belt is composed of thrusted units of different metasedimentary and meta-volcanic formations with various degrees of metamorphism, from high grade to very low grade. These units have recorded three main tectonic phases.

Three main units have been recognized in the Ogooué belt.

2.1.1. The pre-Eburnean migmatites

The pre-Eburnean migmatites are regarded as Archean material affected by partial fusion. These migmatites are similar to those occurring to the west of the Ikoy–Ikobé fault (Lambaréné migmatites). They have been dated at 2450 ± 70 Ma (supplementary material, Table S1; Feybesse et al., 1998; Mayaga-Mikolo, 1996; Thiéblemont et al., 2009a). The migmatites inside the Ogooué complex form the core of a wide anticline structure (Abamié dome) oriented roughly north–south. These formations were submitted to two metamorphic events: the first one at high temperature and the second at high pressure (eclogitic facies with Cpx, Opx, Gt, Pl at 8 Kb, 810 °C) (Feybesse et al., 1998; Thiéblemont et al., 2009a, 2009b). Two U/Pb ages on monazite have been proposed to the two metamorphic peaks, respectively 2208 ± 38 for the HT metamorphism and 2122 ± 43 Ma for the HP metamorphism (Mayaga-Mikolo, 1996). These migmatites have been interpreted either as independent slices of Archean basement mixed together with slices of metamorphic rocks of the Ogooué complex or as the basement of all the tectonic slices of the Ogooué belt (Thiéblemont et al., 2009a). We retain this latter interpretation (see below).

2.1.2. The Ogooué complex

The Ogooué complex itself only occurs in the east of the Ikoy–Ikobé fault (Fig. 1). It is composed of series of metasedimentary formations containing tholeiitic metavolcanic rocks. These formations have been submitted to two metamorphic events, one at high temperature (Bt, Ms, Gt, St, Sill; 6.5 kbar and 610 °C) and the other at high pressure (Ky–Bt–Gr–St, Ilm) at 8 kbar and 550 °C. (Feybesse et al., 1998; Thiéblemont et al., 2009a). In agreement with Thiéblemont et al. (2009a), we retain the Sm/Nd age of 2120 ± 38 Ma for the peak of HP metamorphism (Feybesse et al., 1998) as it is concordant with the age of the HP metamorphism of migmatites. A retrograde metamorphism episode (amphibolite to greenschist facies) is related to a fast adiabatic exhumation of the HP rocks before the intrusion of the Lecoué granite dated at 2009 ± 7 Ma (Thiéblemont et al., 2009a).

2.1.3. The N'Djolé Group

The N'Djolé Group outcrops on the eastern side of the Ikoy–Ikobé fault, and only in two locations. The first one is along the eastern edge of the domain, between the Ogooué complex and the Lopé High (series of Okanda, Figs. 1b), and the second one is located northwest of the Ogooué complex (series of N'Djolé s.s.). This last sedimentary series is made of schistose metasediments, mainly pelites affected by a very low- to low-grade metamorphism. Basic metavolcanites are frequent in the northwestern area. The only age constraint on the N'Djolé Group is provided by zircons from the Ebele region (N'Djolé series), which yield an age of 2118 ± 10 Ma (Thiéblemont et al., 2009a). These authors consider that the deposition of the sediments of the

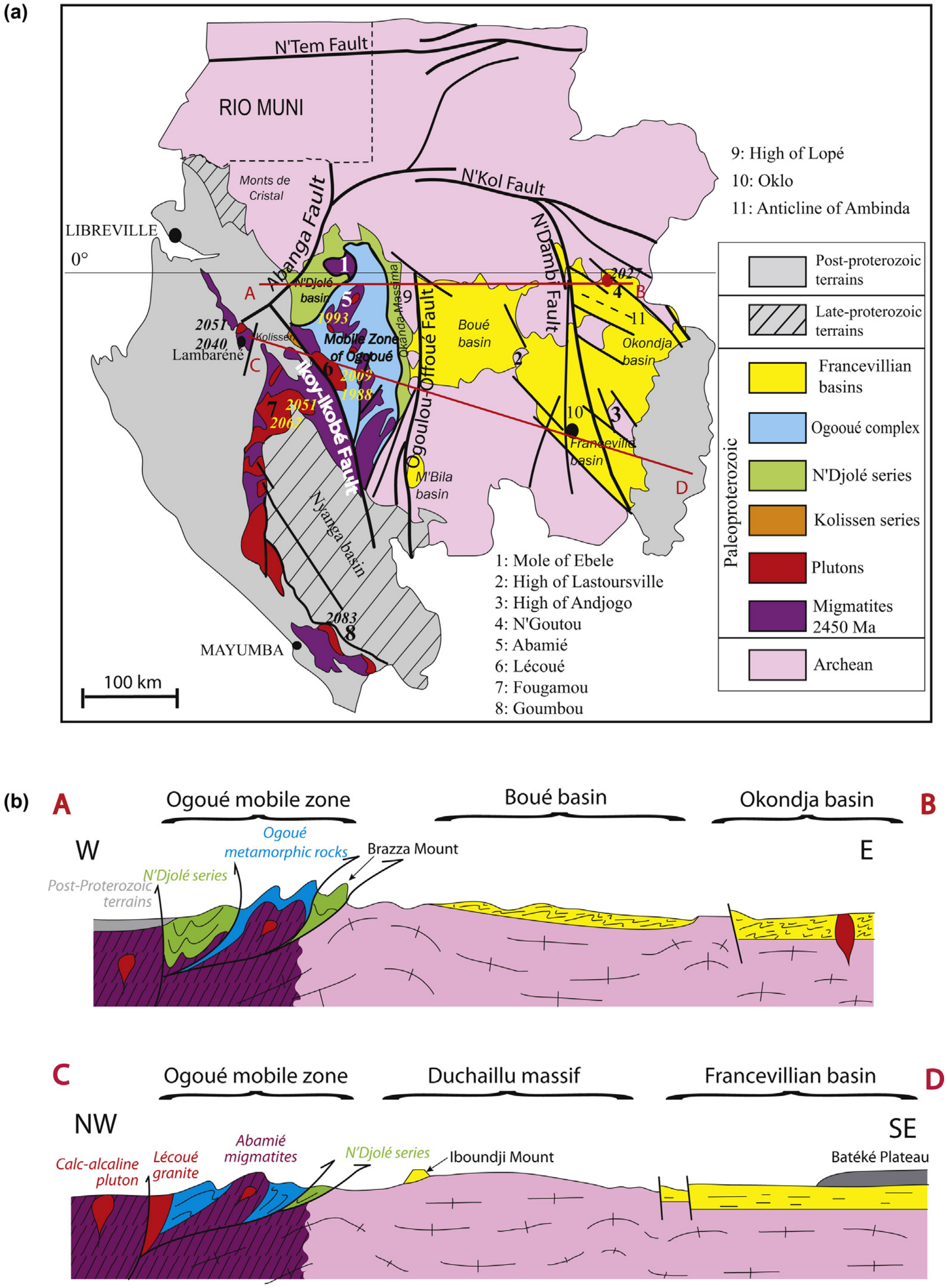

Fig. 1. (a) Schematicgeological map of Gabon. From Thiéblemont et al. (2009a, 2009b), modified. 2083... ages of Eburnean plutons. The lines of the general cross-sections A–B and C–D through the Ogoué mobile zone and the intracratonic basins are shown. (b) General cross-sections from the Eburnean system in Gabon, showing the units of the Ogooué mobile zone and the intracratonic basins of Boué, Franceville, and Okondja.

N'Djolé Group is subsequent to the metamorphic episodes affecting the Ogooué complex. Nevertheless, the series of Okanda to the east of the Ogooué complex, composed of quartzites, sandstones and conglomerates, black shales and cherty quartzites, is considered to be at the base of the group but might be older, taking into account a prograding sedimentation process from east to west.

2.2. Structural relationships between the Ogooué complex and the N'Djolé Group

We observed an important shear zone between the Ogooué complex and the Okanda series of the N'Djolé Group, along the trans-Gabonese railway, at the latitude of equator. North of the Mole of Ebele (around Biboulo),

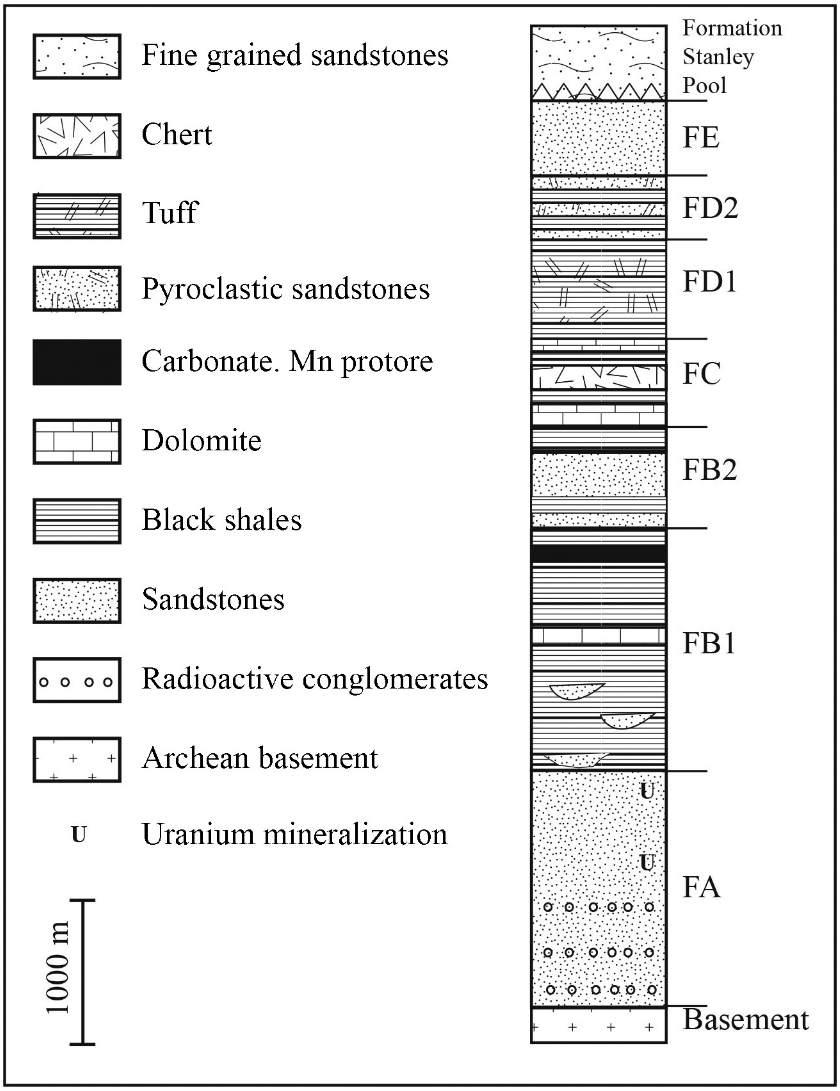

Fig. 2. Shematic lithologic column of the Francevillian series.

Thiéblemont et al. (2009a) described garnet bearing paragneisses of the Ogooué complex overlain tectonically by schists of the N'Djolé Group. The two structural units are clearly in tectonic contact. This pile of units thrusted onto the Archean migmatites has been folded in a large anticlinorium (dome of Abamié) and synclinorium (N'Djolé basin) with NE–SW axes.

Three main phases of deformations D1 to D3 (Feybesse et al., 1998; Gauthier-Lafaye, 1986; Ledru et al., 1994; Thiéblemont et al., 2009a, 2009b) are described. The intensity of the deformation depends on the degree of metamorphism affecting the units (Gauthier-Lafaye, 1986).

In the metamorphic series of lowest grade from N'Djolé and Okanda, the original stratification S0 is deformed (D1) by isoclinal F1 folds, overturned to the ENE and associated with a schistosity S1 bearing mineral paragenesis of the anchizonal zone to greenschist facies. In the east, in the vicinity of the contact with the metamorphic series of the Ogooué complex, the N'Djolé series develop a second schistosity S2 in the axial plane of isoclinal F2 folds, exhibiting mineral parageneses of the greenschist facies.

In the series of the Ogooué complex, the major structures are the F2 isoclinal folds overturned to the ENE, which develop a S2 schistosity dipping to the west and bearing minerals of the amphibolite facies. This S2 cleavage fully transposes all previous structures, including the S1 schistosity linked to the HP metamorphic peak observed in places as relict. The S2 cleavage contains a stretching lineation trending ENE–WSW to NW–SE with kinematic criteria indicating an overall top to the ENE to east transportation (Feybesse et al., 1998; Ledru et al., 1989).

All these structures are affected by a third deformation marked by F3 folds with NS to N50° axes, responsible for the large structures, such as the N'Djolé and Abamié anticlinoriums. This D3 phase locally develops in the series of Ogooué a S3 cleavage of low-degree metamorphism. This third phase would be linked to late strike-slip displacements along the Ikoy–Ikobé and Ogoulou–Offoué major faults. One K/Ar age on a amphibolitic mylonite within the Ikoy–Ikobé fault yields an age of 1970 ± 7 Ma (Corsini et al., 1993). It can reasonably be viewed as the age of the first post-collisional strike-slip motion along the fault.

2.3. Eburnean plutonic intrusions

Depending on the age, the geochemistry and the location, the Eburnean magmatic intrusions are classified in two distinct groups (Thiéblemont et al., 2009a):

- *a western calc-alkaline province* on the west side of the Ikoy–Ikobé fault. They are mainly composed of pink porphyroid granite, granodiorite, tonalite associated with diorite and gabbro. Their age ranges from 2083 ± 25 to 2040 ± 12 Ma (supplementary material, Table S1). The youngest ages are found at Lambaréné, in the North of the province. These granitoids exhibit a shoshonitic composition (Thiéblemont et al., 2009a) involving the melting of lower continental crust and/or metasomatized mantle (Campbell et al., 2014; Küster and Harms, 1998; Morrison, 1980; Turner et al., 1996). The alignment of these plutons, their calc-alkaline nature and their ages, posterior to the HP metamorphism dated at 2120 ± 38 Ma (Feybesse et al., 1998), would suggest that this set of igneous plutons represents intrusive rocks underlying a continental arc above a subduction zone and might have been emplaced after the onset of the collision of the two continental margins (Campbell et al., 2014). This continental arc would have been disrupted by the West Congolian orogeny (900–700 Ma). Therefore, these plutons are distributed on both sides of the Neoproterozoic synclinal of Nyanga (Fig. 1a);
- *an eastern province of hyper-aluminous granite*, on the eastern side of the Ikoy–Ikobé fault intruding the Ogooué belt. These plutons consist of granodiorite in the Lecoué massif, along the eastern side of the Ikoy–Ikobé fault, and of peraluminous porphyroid leucogranite intrusive into the migmatitic Abamié dome and paragneisses of Ogooué. These granitoids are of S-type, and result from the melting of crustal metasediments (Thiéblemont et al., 2009a). They are younger than the granitoids of the western province. The granodiorite of Lecoué intruding the metamorphic rocks and migmatites yield U/Pb and Rb/Sr ages ranging from 2042 ± 8 (Feybesse et al., 1998) to 1980 ± 20 Ma (Cahen-Vachette et al., 1988), but the most recent datings yield U/Pb ages ranging from 1988 ± 9 to 2009 ± 7 Ma (Thiéblemont et al., 2009a). Granites and associated pegmatites intruding the migmatites of the Abamié dome yield ages ranging from 1950 ± 30 Ma (Vachette, 1964) to 1997 ± 7 Ma (Mayaga-Mikolo, 1996); the Mboumi granite yields a U/Pb age of 1993 ± 9 Ma (Thiéblemont et al., 2009a). The intrusion of these granitoids is subsequent to the retromorphic exhumation (1920 ± 35, Mayaga-Mikolo, 1996) and thrusting of the metamorphics. Accordingly, it seals the nappe emplacement of the Ogooué belt.

2.4. Sedimentary formations of the Francevillian intracratonic basins

The sediments are deposited within two main basins, namely Franceville and Okondja. To the west of these sedimentary basins, reduced sedimentary series are observed upon the basement in the Boué and N'Bila areas (Fig. 1a).

The Franceville basin is the best known, due to the occurrence of manganese deposits (Baud, 1954, 1956; Bouladon et al., 1966; Leclerc and Weber, 1980; Weber, 1993) and of uranium deposits (Bourrel and Pfiffelmann, 1972; Gauthier-Lafaye, 1986; Gauthier-Lafaye and Weber, 1989, 2003), which induced important geological surveys and drilling campaigns. Moreover, these basins are certainly among the best preserved of their age on earth. The sediments were deposited at the time of the first oxidation of the atmosphere (Canfield et al., 2013). Apart from the manganese and uranium deposits, two important discoveries assured the reputation of this basin. In 1972, natural nuclear fission reaction zones were discovered in the Oklo uranium deposit (Naudet, 1991; Neuilly et al., 1972). In 2010, the oldest macrofossils ever known on earth were discovered by El Albani et al. (2010, 2014).

The reference stratigraphic column of the sedimentary series has been established in the Franceville basin (Bouton et al., 2009a, 2009b; Donot and Weber, 1968, 1969; Weber, 1968). Five formations have been described, labelled FA to FE from the bottom to the top (Fig. 2).

2.4.1. The Francevillian A (FA)

The Francevillian A (FA) is mainly composed of detrital sediments, quartz–arenite more or less conglomeratic. The top of the formation contains uranium deposits, with the famous Oklo and Mounana deposits. The thickness of the FA formation reaches 1000 m in the Franceville basin. In the Okondja basin, the thickness may also be of several hundred meters. In the Boué and M'Bila areas, the FA formation is thinner than in the main basins, reaching a few tens of meters. Most of the measurements of the current structures show a general flow direction from west to east during the sedimentation of this detrital formation.

In the central part of the Franceville basin, the FA formation evolves from fluvial deposits at the bottom to deltaic and coastal deposits, containing beach and shoreline sand bars facies at the top (Deynoux and Duringer, 1992; Gauthier-Lafaye, 1986).

2.4.2. The Francevillian B (FB)

The Francevillian B (FB) is characterized by an important subsidence. At Oklo, in the basin of Franceville, the transition between the FA and FB formations has been well observed. The sediments start with black silty pelites typical of a transgressive marine sedimentation following the shoreline sandstones of the top of the FA formation (Deynoux and Duringer, 1992). But very soon appear furrowing debris-flows containing dolomitic olistoliths (blocks of several hundred cubic meters) with fragments of cherts and turbidites, revealing a gravity collapse, probably linked to tectonic activity. These result in important and abrupt variations in thickness of this formation, which makes correlations between boreholes difficult. The total thickness of this formation may reach up to 1000 meters in the centre of the basin.

Deposition of black shales follows the main turbidites deposits. It has occurred in a confined and restricted environment resulting in the formation of dolomites that become more and more manganiferous at the top of the formation. These manganese rich carbonate layers are the protore of the Mn deposit of Moanda. Sm–Nd ages on small fractions of clay minerals ($< 0.2\ \mu m$) yield ages of 2099 ± 115 Ma and 2036 ± 70 Ma (Bros et al., 1992; Stille et al., 1993).

Fine-grained siltstones layers in the black shales may contain splintery quartz, rhyolitic quartz exhibiting embayments and well-preserved feldspars and biotites that are likely from volcanic origin (Bouton et al., 2009b). The chemistry of these sedimentary rocks suggests that they derive from the erosion of a continental island arc on an active continental margin (Thiéblemont et al., 2014).

Before the deposition of the stromatolitic cherts (FC), appears a unit (FB2a) of very different composition called "Poubara sandstones". The Poubara sandstone is composed of 1- to 5-m-thick layers of fine-grained and isogranular sandstones with little internal structures if we exclude the dish structures and some angular lithic fragments at the bottom of the layers. These sandstones are interpreted as turbidites that were deposited at a shallow bathymetry with a high energy (El Albani et al., 2010). They immediately precede the emergence of the FC and contain typical sedimentary features indicating a decrease in the water column before and after the deposition of the sandstones (Weber and Gauthier-Lafaye, 2013).

In the Okondja basin, the FB formation is similar to the FB of the Franceville basin. The main difference between these two basins is the presence of basanite, either in massive flows or in pillow-lavas and sills, interstratified with the sediments of the Ambinda anticline, in the northeastern part of the Okondja basin. The volcanism is related to the emplacement of the annular hypo-volcanic alkaline N'Goutou complex (Fig. 1). The plutonic rocks include nephelinic syenites as well as amphibole granite. This structure is associated with a whole set of volcanic and subvolcanic rocks, adjacent to the intrusive complex: syenites, microsyenites and microgranites, pegmatites, trachytes, rhyodacites dykes, sills or lava flows. The N'Goutou complex yields a U–Pb age on zircon of 2027 ± 55 Ma (Moussavou and Edou Minko, 2006).

2.4.3. The Francevillian C (FC)

The Francevillian C (FC) consists of dolomite, often evaporitic (Préat et al., 2011), and of stromatolitic cherts (Bertrand-Sarfati and Potin, 1994; Bouton et al., 2009a, 2009b) interlayered with black shales. This formation corresponds to a very shallow environment almost emerged, linked to a quasi-emersion after the deposition of the FB. In the Franceville and Okondja basins, the top of the FC formation contains layers of pyroclastics with well-characterized splinters of glass (Weber, 1968). The FC formation overlies the pelitic FB formation in the central parts of these basins. In contrast, in Boué and M'Bila areas and on the highs separating the Franceville and Okondja basins, the FC formation rests directly on the FA sandstones and even upon the Archean basement. In these areas, the FC formation is a condensed series, equivalent to the whole FB and FC.

2.4.4. The Francevillian D (FD)

The Francevillian D (FD) in its basal part (FD1) consists of black shales with high organic matter content, devoid of detrital elements and interlayered with pyroclastics. The pyroclastic materials are vitroclastic volcanic ashes containing isolated splinters, made of easily recognizable devitrified glass. They correspond to aerial fallouts from an explosive calc-alkaline, andesitic to ryodacitic volcanism. The calc-alkaline chemistry of these volcanic rocks differs much from the alkaline one associated with the N'Goutou complex, reflecting a different geodynamic context (Thiéblemont et al., 2014).

Horie et al. (2005) attribute a zircon U–Pb age of 2083 ± 6 Ma to a FD ignimbritic flow. Actually, this ignimbritic flow contains inherited zircons with ages between 2825 Ma and 2000 Ma. A reappraisal of the U–Pb data set shows that the age of 2083 ± 6 Ma corresponds to a mixing of two populations of zircon with ages, of 2136–2068 Ma and 2042–2003 Ma, respectively. The youngest age of 2003 ± 16 Ma obtained on a subconcordant zircon could represent the time of emplacement of these pyroclastic flows.

Alternating sequences of dominant sandstones and pelites rest on the lower black shales and pyroclastites (FD2). These sandstones are epiclastic with most of their elements of volcanic origin, with strong acidic character. The deposition of these sandstones seems to be turbiditic. It is suggested that they come from the erosion of volcanic structures.

2.4.5. The Francevillian E (FE)

The Francevillian E (FE) is mainly represented by a 400-m-thick unit of sandstones of the Mount N'Gouadi (Bouton et al., 2009a) where they form several cuestas and a cliff in the syncline of the Loula River, northward of Okondja. The unit contains two megasequences of sandstones. They are coarse sandstones, arkosic, with conglomeratic layers and frequent crossed beddings. Most of these sediments are devoid of reworked volcanic elements (Bouton et al., 2009a), except rare occurrences of ignimbritic pebbles, near Lastoursville and M'Bila (Weber, 1968).

2.5. Structuration of the Francevillian basins

Gauthier-Lafaye (1986) shows that during FB deposition, these sedimentary basins were structured as pull-apart basins between large north–south senestral strike-slip faults. The NW–SE faults, limiting the basins, display vertical offsets up to 400–500 m controlling the FB deposition with various thicknesses. A late strike-slip movement registered by these faults induced wide anticlines and synclines, particularly important in the Okondja basin. Important flexures with a north–south axis, observed in the FA formation of the Oklo region, would suggest that the NS faults might have a normal component during FA deposition.

2.6. Eburnean mined ore deposits

The top of the FA formation contains the famous Oklo and Mounana uranium deposits. The uranium has been transported by oxidizing fluids and reduced by hydrocarbons (asphaltite), which migrated from the FB black shales trapped to the FA sandstones in faulted contacts with the FB formations (Gauthier-Lafaye, 1986). The uranium mineralization is 2050 ± 30 Ma old (Devillers et al., 1975; Gancarz, 1978), and the nuclear fission operated 1950 ± 40 Ma ago (Holliger, 1992; Naudet, 1991; Ruffenach, 1979; Ruffenach et al., 1976).

At the top of the FB formation, the confined environment results in the formation of dolomites that become manganese rich and form the protore of the manganese

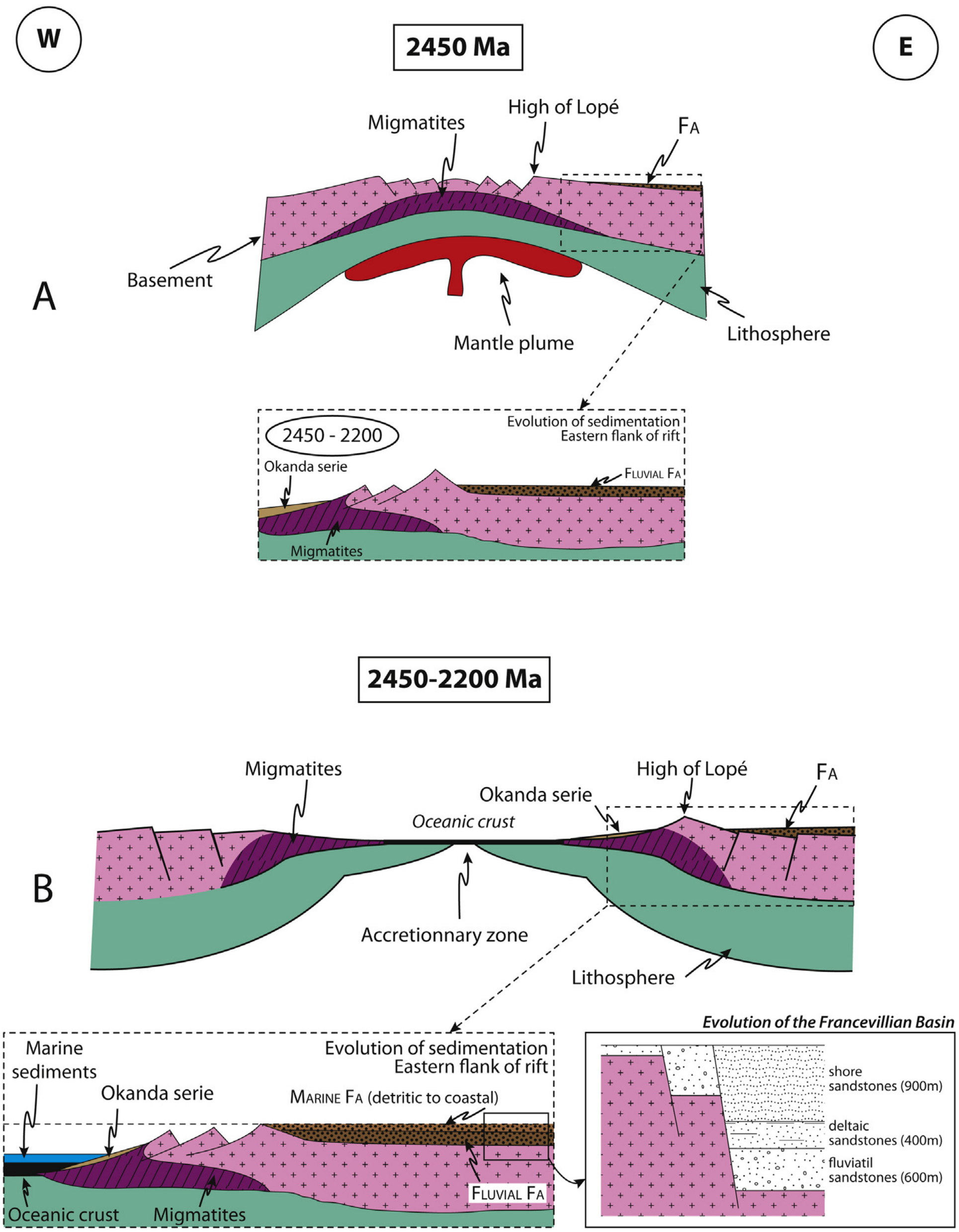

Fig. 3. Conceptual model for the evolution of the Eburnean orogeny in the mobile zone of Ogooué and consequences in sedimentation and magmatic activity in the Francevillian basins. A. The initial rifting stage: the extension of the Archean basement (over a mantle plume?) might be at the origin of the pre-Eburnean migmatites by melting of the continental crustal at 2450 Ma. They constitute the basement of the rift. The High of Lopé is considered to be the eastern shoulder of the rift. Its erosion gave the FA fluvial Francevillian sandstones to the east and the Okanda quartzites at the bottom of the N'Djolé Group to the west. B. During the opening of the ocean, the Okanda marine sediments are deposited on the eastern margin. As the ocean becomes wider, thermal subsidence of the rift shoulders lead to a marine transgression to the east, with the deposition of littoral to marine sediments at the top of the FA formation.

deposit of Moanda, later concentrated in the lateritic formation overlying the carbonates (Leclerc and Weber, 1980; Weber, 1968, 1997).

The primary gold deposits are linked to the Archean greenstone belts. Eburnean post-orogenic hydrothermal remobilization transported and concentrated gold in the Eburnean thrusting contact of the Ogooué belt. The Étéké gold deposit in the Ougoulou–Offoué inverse fault yielded ages ranging from 2100 to 1950 Ma (Feybesse et al., 1998; Prian et al., 1991).

3. Interpretations: towards a new geodynamic scenario

The type of metamorphism in the Ogooué complex and the chemistry of the granitoids of the plutonic belt led the authors of the geological map of Gabon to view the Eburnean orogeny as a continent-continent collision between the San Francisco and West Congolian cratons, after the resorption by subduction of an ocean separating two continental margins (Thiéblemont et al., 2009a). The Ikoy–Ikobé fault would then be a major tectonic structure, viewed as a suture between these two continental lithospheric blocks, along which part of the Ogooué complex would have subducted, and subsequently exhumed and thrusted onto the western Congo craton.

The subduction process should be responsible for the major Eburnean HP metamorphic episode and the intrusion of calc-alkaline plutons in the eastern San Francisco craton. The peak of metamorphism (700–550°, 8–10 Kb) suggests a burial depth of about 25 to 30 km with low thermal gradient, consistent with a subduction regime. In this model, the initial series (Ogooué complex) was deposited on the oceanic floor, tectonically sliced in the accretionary prism and entered partially the subduction channel. The low-grade metasedimentary series of N'Djolé are supposed to have been deposited at the top of the accretionary prism that developed above the oceanic subduction.

The orogeny could be divided into six main steps:

- breakup of an initial single Archean continent, followed by;
- oceanic opening;
- closure of this ocean by subduction of the eastern plate under the western one and opening of the pull-apart Francevillian basins;
- collision of the continental margins of the two Archean blocks and cessation of the sedimentation in the Francevillian basin;
- slab break-off and thrusting of the Ogooué complex;
- post-collision readjustments.

3.1. Initial rifting stage

The first post–Archean episode is the formation of migmatites at 2450 Ma, which took place long after the Late Archean orogeny at 2750 Ma (Fig. 3A). Feybesse et al. (1998) consider that the fusion event could have occurred during a pre-Eburnean orogeny. However, no trace of such an orogeny has been revealed for that period in the region. Thus, we must envisage that this partial fusion of the continental crust has occurred during an "anorogenic" event. An extension of the Archean basement (above a lithospheric delamination or a mantle plume?) followed by crustal upwelling might be at the origin of the crustal melting (Thompson and Connoly, 1995; Whitney et al., 2007; Rey et al., 2009). The north–south alignment of migmatites on each side of the Ikoy–Ikobé fault, observed up to Cameroun, could represent the basement of the rift zone.

The north–south-oriented Archean Lopé High divides the non-metamorphic Francevillian FA formation to the east from the low-degree metamorphic Okanda metasedimentary series at the base of the N'Djolé Group to the west.

The eastwards-directed sedimentary currents measured in the sandstones of the FA formation suggest that the north–south High of Lopé was an elevated horst structure during FA sedimentation. The north–south flexures observed in the FA formation could testify to the activity of normal faults during the deposition of detrital sediments. The High of Lopé might correspond to the eastern shoulder of the rifting zone. The erosion of this elevated horst structure produced the gravel material of the fluvial sandstones at the base of the FA formation and the Okanda series that spreads on each side of the shoulders of the rift. The deposition of FA sandstones, like the basal sandstones of the group of N'Djolé (Okanda quarzites), should begin after the migmatization at 2450 Ma.

3.2. Opening of the ocean and collapse of the margins

The existence of an ocean has been suggested by Thiéblemont et al. (2009a, 2009b) based on the occurrence of tholeiitic basic rocks subsequently affected by the HP metamorphic rocks, associated with oceanic sediments in the Ogooué complex (Fig. 3B). No trace of ophiolite complex has been observed in the region. It is therefore difficult to assess the width of the ocean separating the two continental blocks. Nevertheless, its size should be sufficient to allow the cooling and subduction of the oceanic lithosphere. Anyway, a long period of time is available to create this oceanic lithosphere, between 2450 Ma, the age of the migmatites at the beginning of the rifting, and 2120 ± 38 Ma, the age of the HP metamorphism, linked to the subduction (at least 230 Ma), if we exclude a long period of rifting with the mantle denudation of a maximum of 100 Ma, as suggested by Chenin et al. (2015) for the opening of the Atlantic ocean.

The orientation of the accretion zone should be almost parallel to the north–south-trending continental margins, like in modern oceanic situations. The east–west N'Kol and the N'Tem major faults (Fig. 1) could represent the remaining traces of transform faults that shifted the accretion zone.

As the ocean becomes wider, the mantle heat source moves away from the margins to the mid-ocean ridge. Thermal subsidence of the rift shoulders and isostatic readjustments lead to a marine transgression, at least

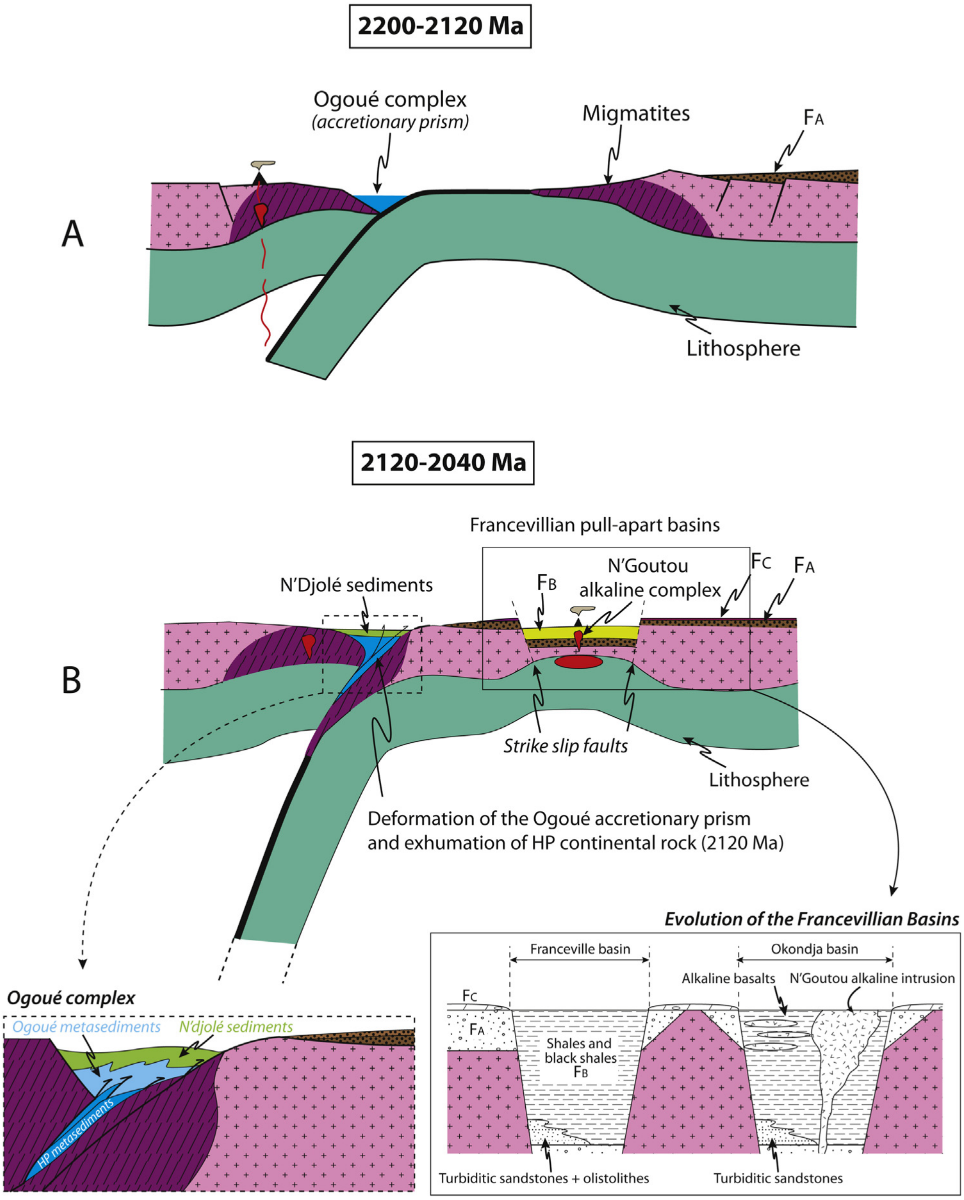

Fig. 4. Conceptual model for the evolution of the Eburnean orogeny in the mobile zone of Ogooué and consequences in sedimentation and magmatic activity in the Francevillian basins (continued). A. The oceanic lithosphere subducts under the western continental plate at 2200 to 2120 Ma; the calc-alkaline plutons intruded in the upper western plate and the sediments at the origin of the Ogoué complex are deposited in the accretionary prism. B. The subduction of the eastern margin of the ocean (2120 to 2040 Ma) blocked the subduction to the south and induced strike-slip movements along the major fault inherited from the rifting stage. These strike-slip movements allow the opening of pull-apart Franceville and Okondja basins filled by turbidites and shales of the FB formation. The N'Goutou alkaline complex intrudes the Okondja. In the Ogooué complex, the metasediments, volcanic rocks and migmatites are transformed in HP metamorphic rocks and exhumed. The N'Djolé series are deposited onto the metamorphic units.

observed on the West Congolian margin to the east of the ocean, with the deposition of littoral marine sediments at the top of the FA formation and the marine N'Djolé sedimentary series.

3.3. Subduction and opening of pull-apart basins

The best witnesses of this subduction are the calc-alkaline plutons, intruded in the upper western plate (Fig. 4). These plutons display ages ranging from 2040 ± 12 to 2080 ± 25 Ma (supplementary material, Table S1).

During the subduction process, the oceanic plate subducts under the western continental plate. The sediments deposited on the oceanic crust form an accretionary prism. The initial series (Ogooué complex) was deposited onto the oceanic floor and tectonically sliced in the accretionary prism and partially entering the subduction channel. They underwent a series of metamorphic events, well described by Feybesse et al. (1998) at

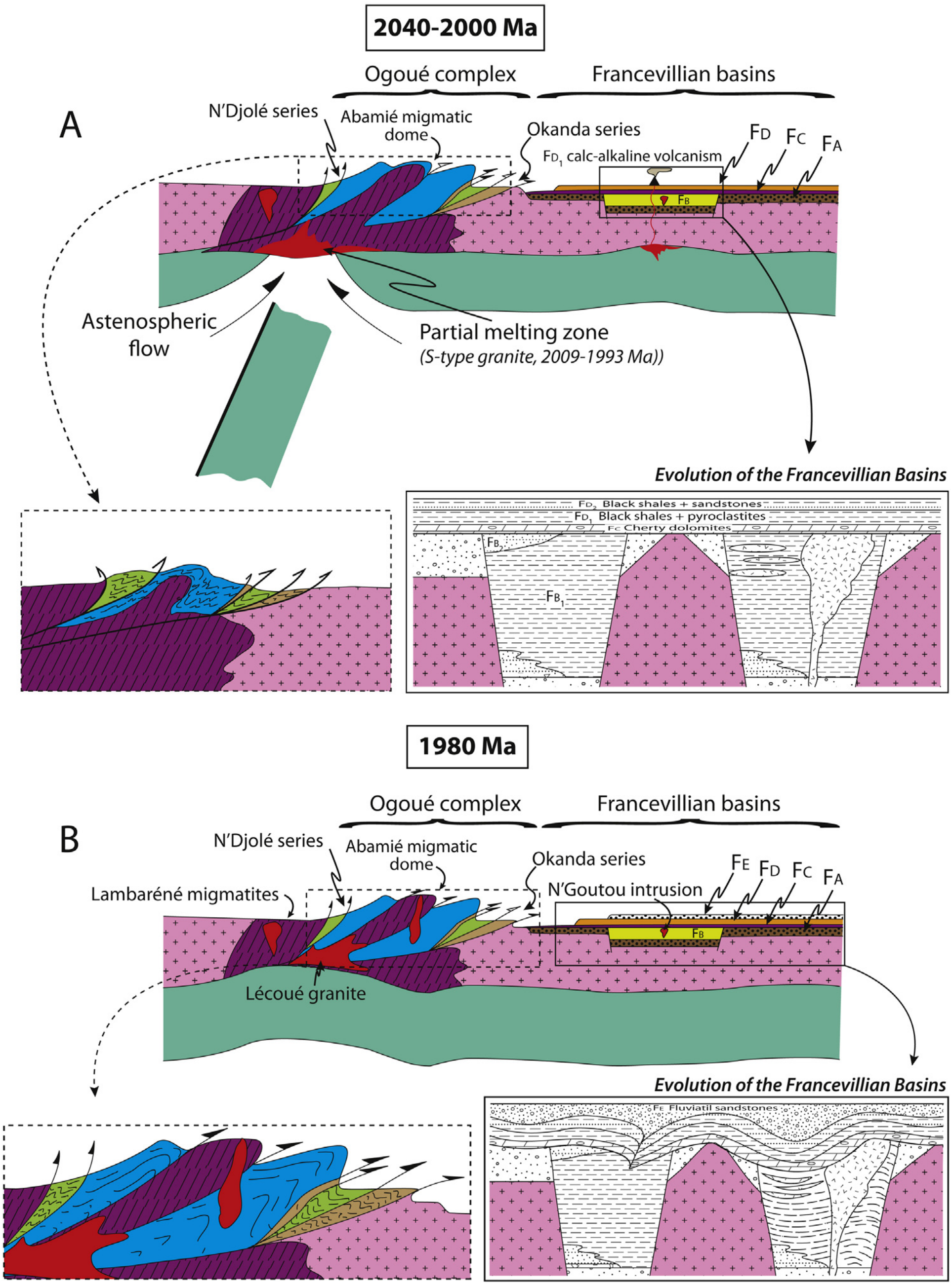

Fig. 5. Conceptual model for the evolution of the Eburnean orogeny in the mobile zone of Ogooué and consequences in sedimentation and magmatic activity in the Francevillian basins (end). A. The continental collision, stop of the subduction (2040 to 2000 Ma). The fast rise of the Ogooué Complex might be the result of a slab break-off. The metamorphic and unmetamorphosed units are thrusted toward the northeast. A hot asthenospheric flow linked to the slab break-off leads to partial fusion within the middle to lower crust, generating the Lecoué granite, which seals the tectonic units of the Ogooué complex. The subsidence of the Francevillian basins ceases to be active and the basins are filled. The FC formation corresponds to a quasi-emersion of the basin. The alkaline magmatic activity in the Okondja basin ceases. After the emersion of the FC, the important transgression FD covers the whole region, after a general collapse of the foreland of the Ogooué complex. The calc-alkaline magmatism observed at the base of the FD formation (FD1) results from partial fusion along deep lithospheric faults. B. At the end of the Eburnean orogeny, the post-collisional adjustments (rotation of blocks) occurring 1950 Ma ago cause important deformations in the basins (mainly in the Okondja basin) and are responsible for the overall emersion. The final erosion of the reliefs produces the FE sandstones.

2120 Ma. The peak of the HP metamorphism (700–550°, 8–10 kbar) corresponds to a burial depth of about 25 to 30 km with a low thermal gradient, consistent with a subduction regime. The age of the peak of metamorphism (2120 ± 38 Ma) agrees well, within the error bars, with the oldest age of the calc-alkaline plutons (2080 ± 25 Ma), linking these two events to the same process of subduction.

Younger ages yielded by the calc-alkaline plutons located in the North (Lambaréné region) indicate that the onset of the collision between the two continental

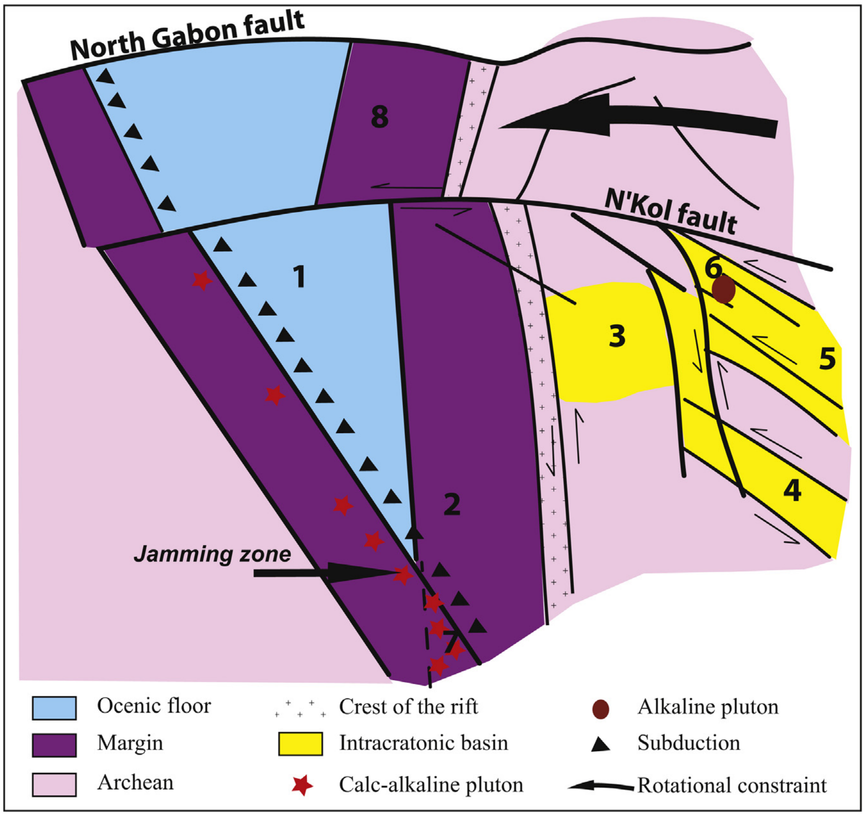

Fig. 6. Schematic diagram of the various domains during the first stage of the collision between the margins: (1) the subduction remains oceanic in the northern part of the ocean; (2) to the south, the margin of the eastern continent is in subduction beneath the western one; this collision results in a rotational constraint inducing strike-slip faults and the opening of the pull-apart Francevillian basins; (3) the Boué basin; (4) the Franceville basin; (5) the Okondja basin; (6) alkaline pluton of N'Goutou; (7) calc-alkaline plutons intruding the San Francisco craton; (8) the margin is shifted a hundred kilometres to the west by the N'Kol fault.

margins would have taken place in the south and ended to the north, implying an oblique subduction. This hypothesis is also supported by the occurrence of an angle of about 30° between the Lopé High, which marks the edge of the old rift, and the fault of the Ikoy–Ikobé fault, which marks the suture between the two plates (Fig. 5).

The HP metamorphism affecting the migmatites of the Abamié dome suggests that the southern part of the margin of the West Congolian craton has been involved in the process of subduction, while in the north, the subduction of the oceanic lithosphere is still active at that time. We hypothesize that the collision of the southern part of the continental margin has induced a general sinistral rotational movement of the cratonic block, probably along the N'Kol fault (Fig. 6). The normal displacements along the north–south faults, during the rifting stage, have shifted during the collision of the southern part of the West Congolian craton to sinistral strike-slip movements. These strike-slip movements have allowed the opening of Franceville and Okondja basins, as pull-apart basins resulting from the strike-slip displacements along the north–south and NW–SE conjugated faults as proposed by Gauthier-Lafaye (1986) (Fig. 6). The Okondja basin has undergone probably more extension than the Franceville basin, allowing the melting of alkaline magma of the N'Goutou complex in the mantle beneath this basin. This event occurred 2027 ± 55 Ma ago, after the peak of HP metamorphism of the Ogooué complex at 2120 ± 38 Ma and before the exhumation of the metamorphic rocks dated at 2009 ± 7 Ma by the retrograde metamorphic reactions.

3.4. *Continental collision and closure of the intracratonic basins*

After the subduction and collision of the eastern margin in the South, the two margins have collided in the area of N'Djolé to the north, and the subduction ceased after 2040 Ma, which is the age of the younger calc-alkaline plutons in the Lambaréné area (Fig. 5A).

The subsidence of the Francevillian basins ceased to be active, the turbiditic sedimentation stopped and the basins were filled by black shales and manganiferous dolomite layers, deposited in a quiet environment, the depth of which was progressively reduced. The alkaline volcanism in the Okondja basin also ceased to be active. The 2027 ± 35 Ma age, marking the end of the plutonic activity of N'Goutou, is almost contemporaneous within the error bars (or just follow) with the age of the youngest Lambaréné calc-alkaline pluton of 2040 ± 12 Ma. This age could correspond to the end of the opening process of the Francevillian basins.

In the meantime, the deformations affecting the Franceville basin create hydrocarbon traps (anticlines and faults) that will be mineralized with uranium for some of them at 2050 ± 30 Ma (Devillers et al., 1975; Gancarz, 1978).

3.5. Slab break-off and emersion of the intracratonic basins

For the authors of the geological map (Thiéblemont et al., 2009a, 2009b), the plutons located east of the Ikoy–Ikobé fault were supposed to have been formed on the western side of the suture, above the subduction, and then drifted during the overthrusting of the Ogooué complex (Fig. 4A). However, this hypothesis is not compatible with the fact that these plutons have different chemical compositions than the western ones. We therefore suggest a different scenario for their formation.

The rapid uplift of the Ogooué Complex with its migmatic substratum recorded in the form of a pervasive retrograde metamorphism of its units could be the result of a slab break-off. The orogenic root rose by isostatic readjustment as often invoked in modern orogens (Westphal et al., 2003). This rapid uplift of the Ogooué complex induced substantial transfer of asthenospheric material from the eastern block toward the suture, at the root of the Ogooué complex. It would be responsible for the melting of the continental crust and the intrusion of the Lécoué granite in the suture (2000 Ma). The thrusting to the northeast of the metamorphic units, as indicated by the D2 overturned folds and associated stretching lineations, is contemporaneous with this isostatic readjustment. The thrusting to the east of the N'Djolé units over the Ogooué complex and of this latter over the autochthon formations of Okanda could mark the end of the process. Probably at the same time, the western part of the basins of Booué was detached from its substratum (Ledru et al., 1989).

Meanwhile, the adiabatic rise of the Ogooué complex locally led to partial fusion within the middle and lower crust. This gave rise to intrusions of scattered small plutons in the Ogooué complex and Abamié dome (M'Boumi granite) around 2000 Ma.

The onset of the uplift to the east of the Ikoy–Ikobé fault would have induced the reworking of the FA sandstones and the deposition, in the Franceville basin, of the FB2a (Poubara sandstones) and FC formations, the FC corresponding to a quasi-emersion of the basins. In the central part of the basins, the deposition of the FB2a and FC formations may have taken place within a very short time, contrary to the condensed series of the FC located on the edges of the basins of Franceville and Okondja.

After the quasi-emersion of the FC formation, the important FD transgression covers the whole region.

The area occupied by the Ogooué complex being about 13,000 km^2, the volume excavated by isostasy is of the order of 150,000 to 200,000 km^3, considering a thickness of the accretionary prism that overcomes 12 to 15 km. We propose that the volume of asthenosphere transferred to the west at the base of the Ogooué complex to compensate its exhumation induced a general subsidence of the foreland to the east (the Francevillian basins). This subsidence was amplified by the overload caused by the thrust of the Ogooué complex and the buckling of the continental lithosphere of the eastern block. The depression created in the foreland would have allowed the FD transgression, which covered whole the Francevillian basin and the basement entirely.

The FD calc-alkaline magmatism occurring at the base of the FD deposits at 2003 Ma is difficult to interpret. This volcanic episode is posterior to the suture between the two continental blocks as the calc-alkaline pyroclastites are observed at the base of the FD. No trace of a new subduction (HP metamorphism) was observed after the intrusions of the N'Goutou complex (2027 ± 55 Ma) at the end of FB and FC. One efficient process to cause the melting of these magmas could have been linked to the reactivation of faults during these isostatic readjustments. The circulations of water, particularly along the large north–south faults, could induce partial melting up to the lower continental crust and even at the top of the mantle (Eyal et al., 2010).

3.6. Hydrothermalism and ore deposit implications

The reactivation of the faults during the isostatic readjustments could have been at the origin of the so-called "post-orogenic hydrothermal circulation" around 2000–1950 Ma. These hydrothermal waters were likely responsible for the silicification of the FC formation. The silicification affected mainly the stromatolites, but also the first levels of cinerites at the top of the cherts (Madjouma River; Weber, 1968) and to a lesser extent the evaporitic dolomites.

The Eburnean gold deposits are associated with the important north–south faults network as in the deposits of Etéké and N'Dambi, which are located along the large Ougoulou-Offoué and N'Dambi strike-slip faults. Gold deposition occurs in quartz veins, viewed as second-order tectonic structures related to the large faults. It has been reworked from a primary source associated with greenstone belts (Thiéblemont et al., 2009a).

The sources of uranium are the Archean granites and the FA sandstones of the Franceville basin. It has been concentrated in the petroleum traps at the top of the FA formation. Uranium percolated through various tectonic structures but the most important deposits, namely Oklo and Mounana are located along a large north–south fault. Here, the hydrothermal circulations along these faults might explain the amount of water necessary to transport uranium toward the deposits (Gauthier-Lafaye, 1986) and the marine origin of the brine, identified in fluid inclusions associated with mineralization (Mathieu et al., 2000).

3.7. End of the Eburnean orogeny

A general isostatic equilibration generated an adjustment of the respective positions of the two continental blocks by a dextral rotation of the western continent (Fig. 5B). This motion triggered the sinistral shear of the Ikoy–Ikobé and Offoué faults together with the dextral shear of N'Kol fault. The K/Ar age of 1970 ± 7 Ma given by Thiéblemont et al. (2009a) for the amphibolitic mylonite of the Ikoy–Ikobé fault dates these late post-collisional strike-slip movements. The D3 folding phase in the Ogooué complex and the N'Djolé Group might be contemporary with these rotations. This marked also the end of the FD transgression, the increase in the compressive stresses in the Franceville and Okondja basins resulting in large folded structures in the Okondja basin and the faulted monoclines in the Franceville basin. At the same time, the diagenetic fluids of the Franceville basin remobilized uranium in the Oklo deposit, resulting in local enrichments where natural nuclear fission reactions started, precisely at the same date, i.e. 1950 ± 50 Ma (Devillers et al., 1991; Gauthier-Lafaye et al., 1989). Finally, the FE formation corresponds to the erosion of the mountain chain of Ogooué.

4. Conclusions

The Eburnean orogeny in Gabon seems to obey to the rules of modern Plate Tectonic, in contrast to Archean orogenies governed by tectonic processes in a hotter Earth.

Thiéblemont et al. (2009a, 2009b), in the most recent edition of the geological map of Gabon, interpret the HP metamorphism of the Ogooué complex as a marker of subduction followed by continental collision. The calc-alkaline nature of the granitic plutons intruding Archean migmatites supports the existence of a subduction zone. The major NNW–SSE transverse fault of Ikoy–Ikobé would be the suture between the two Archean blocks: the San Francisco craton to the west and the Congolian craton to the east.

Three assumptions presented in the above sections lead to a new conceptual model, which integrates the history of the Ogooué belt with the evolution of the Francevillian intracratonic basins:

- the 2450 Ma orthogneisses and migmatites, on each side of the Ikoy–Ikobé tectonic structure, result from the partial melting of the Archean basement during a period of rifting. These migmatites could therefore be regarded as the relicts of the margins of the two continents. The fluvial sandstones of the FA formation at the base of the Francevillian series and in the Okanda series, at the base of the N'Djolé Group, result from the erosion of the rift shoulders. The collapse of the rift shoulders after the continental breakup and the creation of an oceanic lithosphere (at least during 230 Ma) allow the FA marine transgression. Then, the oceanic lithosphere of the eastern plate subducts beneath the western one to generate the HP metamorphic units of the Ogooué complex at 2120 Ma (age of the peak of metamorphism);
- the ages of calc-alkaline plutons intruding the western plate spread from 2080 Ma for the southern intrusions to 2040 Ma for the northern ones. This characteristic is indicative of an oblique subduction. The southern part of the continental margins collided first. This collision blocked the subduction and induced compressional stresses in the eastern craton, resulting in a sinistral strike-slip movement along the north–south faults inherited from the rifting phase. These strike-slip faults opened the pull-apart Francevillian basins, allowing the deposition of the FB marine sediments, intruded by the alkaline N'Goutou complex at 2027 Ma in the Okondja basin. The collision between the two margins propagated towards the north. The widespread emersion of the entire eastern area with the deposition of stromatolithic cherts and evaporitic dolomite of the FC formation was the result of this collision;
- the oceanic lithosphere broke-off from the margin and dived into the mantle. The consequence of this slab break-off was a fast isostatic readjustment to the east of the Ikoy–Ikobé suture and the exhumation of the HP metamorphic units of the Ogooué complex. These units were thrusted to the NNE. This rapid uplift of the orogenic root induces melting and intrusion of granitic plutons scattered in the Ogooué complex. The substantial transfer of asthenospheric material from the eastern block toward the suture would be responsible for the collapse of the eastern block and the FD transgression together with the melting of the crust and intrusion of the Lecoué granite in the suture (2000 Ma). Moreover, hydrated melting along major lithospheric faults beneath the Francevillian basins would have produced the K-calc-alkaline volcanism observed at the base of the FD formation.

Finally, the post-collisional adjustments occurring later, 1950 Ma ago, induce important deformations in the basins, mainly in the Okondja basin and are responsible for the overall emersion. The final erosion of the reliefs produces the FE sandstones.

Acknowledgements

The authors wish to pay tribute to all those who contributed to the geology of Gabon in a country where the working conditions are particularly difficult for geologists. We thank all participants in the SYSMIN program without whom this work would not have been possible, Pascal Bouton who introduced us to this program, and Denis Thiéblemont, the coordinator who kindly read and commented our first draft. Thanks also to Olabode Bankole and an anonymous reader who kindly read the manuscript to improve the English. Finally, we thank Pierre Barbey and Jacky Ferrière, who accepted to review the first draft, and Isabelle Manighetti for editorial comments that helped us to improve the manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.crte.2016.07.003.

References

Baud, L., 1954. Carte géologique de reconnaissance au 1/500 000, feuille de Franceville et avec notice explicative. Bull. Dir. Mines et Geol. A.E.F., Brazzaville (43 p.).

Baud, L., 1956. Les gisements et indices de manganèse de l'A.E.F.In: XXe Congr. Géol. Intern., Mexico, Symp. Mn II. pp. 21–30.

Bertrand-Sarfati, J., Potin, B., 1994. Microfossiliferous cherty stromatolites in the 2000 Ma Franceville Group, Gabon. Precamb. Res. 65, 341–356.
Bouladon, J., Weber, F., Veysset, C., Favre-Mercuret, R., 1966. Sur la situation géologique et le type métallogénique du gisement de manganèse de Moanda, près de Franceville (République gabonaise). Bull. Serv. Carte Geol., Als. Lorr. fasc. 4, 253–276.
Bourrel, J., Pfiffelmann, J.-P., 1972. La province uranifère du bassin de Franceville (République gabonaise). Mineral. Deposit. 7, 323–336.
Bouton, P., Thiéblemont, D., Gouin, J., Cocherie, A., Guerrot, C., Tégyey, M., Préat, A., Simo-Ndounze, S., Moussavou, M., 2009a. Notice explicative de la carte géologique de la république du Gabon à 1/200 000, feuille d'Okondja. Édition DMG, ministère des Mines, du Pétrole, des Hydrocarbures, Libreville (76 p.).
Bouton, P., Thiéblemont, D., Gouin, J., Cocherie, A., Guerrot, C., Tégyey, M., Préat, A., Simo-Ndounze, S., Kassadou, A.B., Boulingui, B., Ekogha, H., Moussavou, M., 2009b. Notice explicative de la carte géologique de la république du Gabon à 1/200 000, feuille Franceville–Boumango. Édition DMG, ministère des Mines, du Pétrole, des Hydrocarbures, Libreville (79 p.).
Bros, R., Stille, P., Gauthier-Lafaye, F., Weber, F., Clauer, N., 1992. Sm-Nd isotopic dating of Proterozoic clay material. Example from Francevillian sedimentary Series (Gabon). Earth Planet. Sci. Lett. 113, 207–218.
Cagnard, F., Barbey, P., Gapais, D., 2011. Transition between "Archaean-type" and "modern-type" tectonics: insights from the Finnish Lapland Granulite Belt. Precamb. Res. 187, 127–142.
Cahen-Vachette, M., Vialette, Y., Bassot, J.P., Vidalv, P., 1988. Apport de la géochronologie isotopique à la connaissance de la géologie gabonaise. Chron. Rech. Min. 491, 35–54.
Campbell, I.H., Stepanov, A.S., Liang, H.Y., Allen, C.M., Norman, M.D., Zhang, Y.Q., Xie, Y.W., 2014. The origin of shoshonites: new insights from the Tertiary high-potassium intrusions of eastern Tibet. Contrib. Mineral. Petrol. 167, 983.
Canfield, D.C., Ngombi-Pemba, L., Hammarlun, E.U., Bengtson, S., Chaussidon, M., Gauthier-Lafaye, F., Meunier, A., Riboulleau, A., Rollion-Bard, C., Rouxel, O., Asael, D., Pierson-Wickmann, A., El Albani, A., 2013. Oxygen dynamics in the aftermath of the Great Oxidation of Earth's atmosphere. Proc. Natl. Acad. Sci. U S A 110, 16730–16735.
Cawood, P.A., Tyler, I.M., 2004. Assembling and reactivating the Proterozoic Capricorn Orogen: lithotectonic elements, orogenies, and significance. Precamb. Res. 128, 201–218.
Cawood, P.A., Kröner, A., Highway, S., Pisarevsky, S., 2006. Precambrian plate tectonics: criteria and evidence. GSA Today 16, 4–11.
Chenin, P., Manatschal, G., Lavier, L.L., Erratt, D., 2015. Assessing the impact of orogenic inheritance on the architecture, timing and magmatic budget of the North Atlantic rift system: a mapping approach. J. Geol. Soc. 172, 711–720.
Choubert, B., 1954. Recherche géologique du Gabon central. Bull. Dir. Mines Geol. A.E.F. 6, 7–91.
Cook, F.A., van der Velden, A.J., Hall, K.W., Roberts, B.J., 1999. Frozen subduction in Canada's Northwest Territories; lithoprobe deep lithospheric reflection profiling of the western Canadian Shield. Tectonics 18, 1–24.
Condie, K.C., 1986. Geochemistry and tectonic setting of Early Proterozoic supracrustal rocks in the southwestern United States. J. Geol. 94, 845–864.
Condie, K.C., 2005. Earth as an Evolving Planetary System. Academic Press, Elsevier (447 p.).
Corsini, M., Ruffet, G., Féraud, G., 1993. Contraintes géochronologiques par analyses $^{39}Ar/^{40}Ar$ sur le fonctionnement de la zone de décrochement ductile de l'Ikoye–Ikobé (Gabon) au cours du Protérozoïque. C. R. Acad. Sci. Paris, Ser. II 317, 531–536.
Cosson, J., 1956. Coupure géologique Port-Gentil Est. Bull. Dir. Mines Geol. A.E.F. 7, 47–52.
Cosson, J., 1957. Données nouvelles sur le système de l'Ogooué et les roches cristallines associées. Bull. Dir. Mines Geol. A.E.F. 8, 21–32.
Cosson, J., 1961. Reconnaissance géologique de la région centrale de la coupure Port-Gentil Est (Gabon). Bull. Inst. Equat. Rech. Geol. Min. 14, 10–14.
Devillers, C., Ruffenach, J.-C., Ménès, L., Lucas, M., Hagemann, R., Nief, G., 1975. Âge de la minéralisation de l'uranium et date de la réaction nucléaire. In: Le phénomène d'Oklo, I.A.E.A., STI/PUB/405. AIEA, Wien, Vienna, 293–302.
Deynoux, M., Duringer, P., 1992. Étude sédimentologique du gisement d'uranium d'Oklo–Okelobondo. Protérozoïque inférieur du bassin de Franceville, Gabon. Internal report. CGS–ULP, Strasbourg (35 p.).
Donot, M., Weber, F., 1968. Carte géologique de reconnaissance au 1/500 000, feuille Franceville-est avec notice explicative. Première édition. Ministère des Mines, Ressources Hydraul., Energ., Gabon, Éd. BRGM France (43 p., 1 carte couleur et rapport BRGM 68 RME 049).
Donot, M., Weber, F., 1969. Carte géologique de reconnaissance au 1/500 000, feuille Franceville-ouest avec notice explicative. Première édition. Ministère des Mines, Ressources Hydraul., Energ., Gabon, Éd. BRGM France (55 p. + 1 carte couleur et rapport BRGM 68 RME 050).
El Albani, A., Bengton, S., Canfield, D.E., Bekker, A., Miacchiarelli, R., Mazurier, A., Hammarlund, E.U., Boulvais, P., Dupuy, J.J., Fontaine, C., Füsi, F.T., Gauther-Lafaye, F., Janvier, P., Javaux, E., Ossa-Ossa, F., Pierson-Wickmann, A.C., Riboulleau, A., Sardini, P., Vachard, D., Whitehouse, M., Meunier, A., 2010. Large colonial organisms with coordinated growth in oxygenated environments 2.1 billion years ago. Nature 466, 100–104.
El Albani, A., Bengtson, S., Canfield, D.E., Riboulleau, A., Rollion-Bard, C., Macchiarelli, R., Ngombi-Pemba, L., Hammarlund, E., Meunier, A., Moubiya Mouele, I., Benzerara, K., Bernard, S., Boulvais, P., Chaussidon, M., Cesari, C., Fontaine, C., Chi-Fru, E., Garcia Ruiz, J.-M., Gauthier-Lafaye, F., Mazurier, A., Pierson-Wickmann, A.-C., Rouxel, O., Trentesaux, A., Vecoli, M., Versteegh, G., White, L., Whitehouse, M., Bekker, A., 2014. The 2.1 Ga Old Francevillian biota biogenicity, taphonomy an biodiversity. PLoS One 9 (6), e99438, http://dx.doi.org/10.1371/journal.pone.0099438.
Eyal, M., Litvinovsky, B., Jahn, B.M., Zanvilevich, A., Katzir, Y., 2010. Origin and evolution of post-collisional magmatism: Coeval Neoproterozoic calc-alkaline and alkaline suites of the Sinai Peninsula. Chem. Geol. 269, 153–179.
Feybesse, J.-L., Johan, V., Triboulet, C., Guerrot, C., Mayaga-Mikolo, F., Bouchot, V., Eko N'dong, J., 1998. The West Central African belt: a model of 2.5–2.0 Ga accretion and two-phase orogenic evolution. Precamb. Res. 87, 161–216.
Gancarz, A.J., 1978. U-Pb age (2.05×109 years) of the Oklo uranium deposit. In: Natural Fission Reactors, AIEA-TCSTI/PUB/475, AIEA, Wien, Vienna, pp. 513–520.
Gapais, D., Jaguin, J., Cagnard, F., Boulvais, P., 2014. Pop-down tectonics, channelling and ore deposits within ancient hot orogens. Tectonophysics 618, 102–106.
Gauthier-Lafaye, F., 1986. Les gisements d'uranium du Gabon et les réacteurs d'Oklo. Modèle métallogénique de gîtes à fortes teneurs du Protérozoïque inférieur. Mem. Sci. Geol. 78, (206 p.).
Gauthier-Lafaye, F., Weber, F., 1989. The Francevillian (Lower Proterozoic) uranium ore deposits of Gabon. Econ. Geol. 84, 2267–2285.
Gauthier-Lafaye, F., Weber, F., 2003. Natural nuclear fission reactors: time constraints for occurrence and their relation to uranium and manganese deposits and to the evolution of the atmosphere. Precamb. Res. 120, 81–101.
Gauthier-Lafaye, F., Weber, F., Ohmoto, H., 1989. Natural fission reactors of Oklo. Econ. Geol. 84, 2286–2295.
Holliger, P., 1992. Les nouvelles zones de réaction d'Oklo : datation U-Pb et caractérisation in-situ des produits de fission à l'analyseur ionique. Technical report DEM No. 01/92. CEREM, Grenoble, France (42 p.).
Horie, K., Hidaka, H., Gauthier-Lafaye, F., 2005. U-Pb geochronolog and geochemistry of zircon from the Franceville series at Bidoudouma, Gabon. Geochim. Cosmochim. Acta 69 (10), A11.
Korja, A., Heikkinen, P., 2005. The accretionary Svecofennian orogen—insight from the BABEL profiles. Precamb. Res. 136, 241–268.
Kröner, A., 1985. Ophiolites and the evolution boundaries in the Late Proterozoic Arabian-Nubian Shield of Northeast Africa and Arabia. Precamb. Res. 27, 277–300.
Küster, D., Harms, U., 1998. Post-collisional potassic granitoids from the southern and northwestern parts of the Late Neoproterozoic East African Orogen: a review. Lithos 45, 177–195.
Leclerc, J., Weber, F., 1980. Geology and genesis of the Moanda manganese deposits, Republic of Gabon. Proc. XXVth Intern. Congr. Geology, Sydney (1976). In: Varensov, I.M., Gaassell, G.Y. (Eds.), Geology and Geochemitry of Manganese, 2. Schweitzerbart'sche Verl, Stuttgart, Germany, pp. 89–109.
Ledru, P., Eko N'Dong, J., Johan, V., Prien, J.-P., Coste, B., Haccard, D., 1989. Structural and metamorphic evolution of the Gabon orogenic belt: collision tectonics in the Lower Proterozoic? Precamb. Res. 44, 227–241.
Ledru, P., Johan, V., Milési, J.P., Tegyey, M., 1994. Markers of the last stages of the Palaeoproterozoic collision: evidence for a 2 Ga continent involving circum-South Atlantic provinces. Precamb. Res. 69, 169–191.
Lerouge, C., Cocherie, A., Toteu, S.F., Penaye, J., Milési, J.-P., Tchameni, R., Nsifa, E.N., Fanning, C.M., Deloule, E., 2006. Shrimp U–Pb zircon age evidence for Paleoproterozoic sedimentation and 2.05Ga syntectonic plutonism in the Nyong Group, southwestern Cameroon: consequences for the Eburnean–Transamazonian belt of NE Brazil and Central Africa. J. Afr. Earth Sci. 44, 413–427.

Mathieu, R., Cuney, M., Cathelineau, M., 2000. Geochemistry of palaeo-fluids circulation in the Franceville basin and around Oklo natural nuclear reaction zones (Gabon). J. Geochem. Explor. 69–70, 245–249.

Mayaga-Mikolo, F., 1996. Chronologie des évènements sédimentaires, magmatiques et tectono-métamorphiques du Précambrien d'Afrique centrale occidentale (Gabon). Tectonogenèse Ogooué et héritage Archéen. (Thèse de doctorat d'université). Univ. Blaise-Pascal, Clermont-Ferrand-1 (185 p.).

Möller, A., Appel, P., Mezger, K., Schenk, V., 1995. Evidence for a 2 Ga subduction zone: eclogites in the Usagarian belt of Tanzania. Geology 23, 1067–1070.

Morrison, G.W., 1980. Characteristics and tectonic setting of the shoshonite rock association. Lithos 13, 79–108.

Moussavou, M., Edou Minko, A., 2006. Contribution à l'histoire thermo-tectonique précambrienne du complexe annulaire de N'goutou par la géochimie et la géochronologie U/Pb sur minéraux accessoires (Bassin Francevillien d'Okondja, Gabon). Afr. Geosci. Rev. – Bassins Afr. – Biogeosci. Environ. 13 (1), 53–62.

Moyen, J.-F., Hunen, J., 2012. Short-term episodicity of Archaean plate tectonics. Geology 40, 451–454.

Naudet, R., 1991. Oklo : des réacteurs nucléaires fossiles – étude physique. Série Synthèses: CEA. Éditions Eyrolles, Paris (685 p.).

Neuilly, M., Bussac, J., Frejacques, C., Nief, G., Vendryes, G., Yvon, J., 1972. Sur l'existence dans un passé reculé d'une réaction en chaîne naturelle de fission, dans le gisement d'uranium d'Oklo (Gabon). C. R. Acad. Sci. Paris, Ser. D 275, 1847–1849.

Préat, A., Bouton, P., Thiéblemont, D., Prian, J.-P., Ndounze, S.S., Delpomdor, F., 2011. Paleoproterozoic high δ13C dolomites from the Lastoursville and Franceville s (SE Gabon): stratigraphic and synsedimentary subsidence implications. Precamb. Res. 189, 212–228.

Prian, J.-P., Eko, N'Dong, J., Coste, B., 1991. Synthèse géologique et géochimique, potentialités minières du degré carré Mouila (Archéen et Protérozoïque du Gabon central), avec carte géologique à 1/200 000. Synthèse du district aurifère d'Etéké. Éd. BRGM pour DGMG Gabon. Vol. 1 (212 p.).

Rey, P.-F., Teyssier, C., Whitney, D.L., 2009. The role of partial melting and extensional strain rates in the development of metamorphic core complexes. Tectonophysics 477, 135–144.

Ruffenach, J.-C., Ménès, L., Devillier, C., Lucas, M., Hagemann, R., 1976. Études chimiques et isotopiques de l'uranium, du plomb et de plusieurs produits de fission dans un échantillon de minerai du réacteur naturel d'Oklo. Earth Planet. Sci. Lett. 30, 94–108.

Ruffenach, J.-C., 1979. Les réacteurs naturels d'Oklo. Paramètres neutroniques, date et durée de fonctionnement, migrations de l'uranium et des produits de fission. (Thèse). Univ. Paris-5 (351 p.).

Stille, P., Gauthier-Lafaye, F., Bros, R., 1993. The neodymium isotope system as a tool for petroleum exploration. Geochim. Cosmochim. Acta 57, 4521–4525.

Thiéblemont, P., Castaing, C., Billa, M., Bouton, P., Préat, A., 2009a. Notice explicative de la carte géologique et des ressources minérales de la République gabonaise au 1/1000 000. Éditions BRGM – ministère des Mines, du Pétrole, des Hydrocarbures, Libreville (381 p.).

Thiéblemont, P., Castaing, C., Bouton, P., Billa, M., Prian J.-P., Goujou J.-C., Boulingui B., Ekogha, H., Kassadou, A.B., Simo-Ndounze, S., Ebang-Obiang, M., Nagel, J.-L., Abouma-Simba, S., Husson, Y., 2009b. Carte géologique et des ressources minérales de la République gabonaise au 1/1 000 000. Éd. BRGM – ministère des Mines, du Pétrole, des Hydrocarbures, Libreville.

Thiéblemont, D., Pascal Boutonn, P., Préat, A., Goujou, J.-C., Tegyey, M., Weber, F., Ebang-Obiang, M., Joron, J.-L., Treuil, M., 2014. Transition from alkaline to calc-alkaline volcanism during evolution of the Paleoproterozoic Francevillian basin of eastern Gabon (Western Central Africa). J. Afr. Earth Sci. 99, 215–227.

Thompson, A.B., Connoly, J.A.D., 1995. Melting of the continental crust: some thermal and petrological constraints on anatexis in continental collision zones and other tectonic settings. J. Geophys. Res. 100 (B8), 15565–15579.

Turner, S., Arnaud, N., Liu, J., Rogers, N., Hawkesworth, C., Harris, N., Kelley, S., Van Calsteren, P., Deng, W., 1996. Post-collision, shoshonitic volcanism on the Tibetan Plateau: implications for convective thinning of the lithosphere and the source of ocean island basalts. J. Petrol. 37, 45–71.

Vachette, M., 1964. Âge radiométrique des formations cristallines d'Afrique équatoriale (Gabon, République centrafricaine, Tchad, Moyen Congo). Ann. Fac. Sci. Univ. Clermont-Ferrand 25 (8), 31–38.

Weber, F., 1968. Une série précambrienne du Gabon : le Francevillien. Sédimentologie, géochimie et relation avec les gîtes minéraux associés. Mem. Serv. Carte Geol. Als. Lorr. 28, 328 p.

Weber, F., 1993. Les gisements latéritiques de manganèse. In: Paquet, H., Clauer, N. (Eds.), Sédimentologie et géochimie de la surface. Colloque à la mémoire de Georges Millot. Éd. Académie des Sciences, Paris, pp. 77–99.

Weber, F., 1997. Evolution of lateritic manganese deposits. In: Paquet, H., Clauer, N. (Eds.), Soils and Sediments, Mineralogy and Geochemistry. Springer, Heidelberg, Germany, pp. 97–124.

Weber, F., Gauthier-Lafaye, F., 2013. No proof from carbon isotopes in the Francevillian (Gabon) and Onega (Fennoscandian shield) basins of a global oxidation event at 1980–2090 Ma following the Great Oxidation Event (GOE). C. R. Geoscience. 345, 28–35.

Westphal, M., Whitechurch, H., Munschy, M., 2003. La tectonique des plaques. GB Science Publisher, Paris (307 p.).

White, D.J., Lucas, S.B., Bleeker, W., Hajnal, Z., Lewry, J.F., Zwanzig, H.V., 2002. Suture-zone geometry along an irregular Paleoproterozoic margin: the superior boundary zone, Manitoba, Canada. Geology 30, 735–738.

Whitney, D.L., Teyssier, C., Heizler, M.T., 2007. Gneiss domes, metamorphic core complexes, and wrench zones: thermal and structural evolution of the Nigde Massif, central Anatolia. Tectonics 26, TC5002.

Windley, B.F., 1995. The Evolving Continents, third ed. John Wiley & Sons, Chichester (526 p.).

Zhao, G., Cawood, P.A., Wilde, S.A., Sun, M., 2002. Review of global 2.1–1.8 Ga orogens: implications for a pre-Rodinia supercontinent. Earth Sci. Rev. 59, 125–162.